INVESTIGATION OF DAMAGE IN KEVLAR / EPOXY COMPOSITES USING ACOUSTIC EMISSION TECHNIQUE

by

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CERTIFICATE

This is to certify that the thesis entitled, INVESTIGATION OF DAMAGE IN KEVLAR/EPOXY COMPOSITES USING ACOUSTIC EMISSION TECHNIQUE by D.S. Rajan is a record of the work carried out under our supervision and has not been submitted elsewhere for a degree.

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To My

Loving Parents

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NOMENCLATURES

Σ : Summation

$\bar{X}$: Mean

σ : Standard deviation

M · Skewness

K : Kurtosis

$\bar{X}_{PA}$: Mean of Peak amplitude

σ_{PA} : Standard deviation of Peak amplitude

$\bar{X}_{ED}$: Mean of Event duration

σ_{ED} : Standard deviation of Event duration

ABSTRACT

Acoustic emissions are sound waves produced by rapid release of energy, caused due to internal local failures within a material. When failure mechanisms are complex as in composite materials, acoustic emission can be an effective non- destructive technique for the detection of defects.

In the present work damage analysis of Kevlar/ epoxy composites through Acoustic Emission Technique [AET] has been done. The Acoustic Emission [AE] data recorded in real time on AET microcomputer based monitoring system is available in the form of event listing. Three computer softwares have been developed for specific data interpretation and analysis . The software coded 'STATPRO' helps to analyze and plot the data statistically for five AE parameters. The software coded 'HISTPRO' helps to obtain the data in graphical form in terms of histogram displays. The third software coded 'CROSSPRO', helps to obtain listing of events in various forms, represent graphically crossplots and/or statistical based cluster plot of any two AE parameter. Attention is based on determining the methodology for an analysis with an end aim of selecting the best AE parameters that categorize the specific failure processes.

Investigations have been carried out on Kevlar/Epoxy laminates of $[0_{12}]$, $[90_{12}]$, $[45_{12}]$, $[0_3/90_3]_s$, $[90_3/0_3]_s$, and pure epoxy sample and high fiber volume laminates. The laminates and epoxy samples were fabricated in the laboratory and single edge notched specimens were prepared. The tests were conducted on a 10

tonne MTS-810 system interfaced to AET-5000 system. It has been observed through statistical analysis that two AE parameters Peak amplitude [PA] and Event duration [ED] are best indicators to classify matrix failure and fiber failure. The extent of matrix failure and fiber failure has been found to be less than the interface failure.

As a step in improving the AE data postprocessing efficiency, data transfer from the NorthStar CP/M computer system and MS-DOS PC has also been done.

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION :

Composite materials are based on the controlled distribution of one or more materials, the reinforcement,in the continues phase of a second material, the matrix. Today, fiber composites find widespread application ranging from sporting goods to spacecraft components. Composite materials, due to their orthotropic properties and heterogeneity, require part by part evaluation to ensure that a component is reliable and will perform as intended. Non-destructive test methods developed for metallic structures may be difficult to apply directly to composite materials, hence modification or development of entirely new methods are often required .

Non-Destructive Testing [NDT] detects discontinuities in materials. But most of the commercially established NDT techniques cannot judge the injurious nature of a defect. All efforts in improving the present NDT techniques are towards extracting more information about the flaw so that the design engineer can decide about the acceptability of the defect. Also none of the present NDT technique gives real-time information regarding flaw initiation or growth . Acoustic Emission [AE] technique promises to fill up the above gap in NDT technology.

The application of stress or temperature field to a composite material results in elastic energy being stored in the material. The sudden local release of such energy is the basic cause of the AE from the material. For this AE to be observable,

it must occur over a short enough period of time and be sufficient to generate a stress wave , that reaches the AE transducer with enough magnitude to cause an output above the noise level. The local energy release is an "AE Event" and the signal that comes out of the AE transducer the "AE" [1].

1.2 STATE-OF-THE-ART :

Acoustic Emission as a NDE tool is a technique to check for the most common flaws in material. When several micro-fracture processes occur simultaneously during flaw growth, such as matrix crazing, fiber matrix debonding and inter laminar cleavage, the statistical distribution in the value of the AE parameters generally overlap so that identification of an individual AE signal being caused by a particular process is not possible . However statistical evaluation of the data for a few hundred events in terms of the analytical distribution should provide a quantitative measure of the relative amounts of the various processes which occurred .

Generally, the AE event count , the AE event rate , the AE peak amplitude , the AE duration are used as AE parameters. Analysis of AE signature is discussed in this investigation using these parameters .

Since the first successful application of AE technique on polaris missile chamber [2], extensive research is being carried out to utilize its potential as a reliable methods for testing ,inspection and evaluation . The rapid advancement in signal processing has led to the development of commercial acoustic emission equipments and systems which help to evaluate the

severity of a source and obtain warning before imminent failure of the structure .

In 1971 , pollock [3] directed his research towards practical application of AE for material testing and NDT. Later large number of investigators initiated laboratory investigation into the AE phenomenon. While a fair amount of results have been established on application of AE to metals , in case of fiber composite , due to the heterogeneity and intricate failure process no distinct quantitative results have been established .

Hamstad's [4] work on monitoring AE in fiber composites acts as a comprehensive guide to know about some fundamental failure processes .

Brown [5] investigated AE from specimens of glass reinforced plastic. His emphasis was on the use of AE for material assessment rather than for defect location . He conducted tensile test on different specimen , classified in terms of matrix type (epoxy or polyester), resin hardener ratio and density of reinforcement . He used ringdown counts as the parameter for his analysis and quantified the results through statistical methods He concluded that ringdown count may be a more dispersive quantity than are the macroscopic physical properties of the specimen .

Williams Jr et al. [6] used statistical analysis procedure to distinguish the different predominant failure mechanism in graphite epoxy specimens. They inferred that even with a single specimen , an incremental change in stress may initiate from different sources . Thus it is extremely unlikely

that any direct comparison between a single AE event and another AE event will enable source mechanism discrimination . Therefore, groups of AE events are treated as random data and statistically analyzed to identify group characteristic which enable mechanism discrimination .

Prasanna Kumar et al. [7] used AE as a material testing tool to test aluminum base alloys through amplitude distribution analysis , statistical analysis and time series analysis . Through the study of mean , standard deviation , skewness and kurtosis they differentiated the mechanism causing AE in pored and porefree castings.

Graham [8,9] used AE to analyze the signature of graphite epoxy composite specimens and made empirical observation relating to frequency content and amplitude distribution . He then used statistical analysis , multiparameter correlation and pattern recognition technique to identify distinct type of AE events.

Hamstad [1] investigated using frequency analysis technique for locating AE source in kevlar/epoxy composite pressure vessel . He established that large signal propagation losses and a dynamic range of AE burst signal results in significant difficulties for determining the criticality of AE source events in fiber composites.

Abdul majid [10] applied unsupervised pattern classification technique to investigate source characterization of AE signals . He observed that by using the threshold-K-means method the sources can be characterized and feasibility for pattern recognition exist .

Moore et al. [11] carried out tests and monitored AE during single filament tension tests on kevlar-49 fibers. They studied the behaviour of dry and wet fiber bundles. They conducted statistical studies on the AE parameters for characterization of the source mechanism in filament failure. The mean ,standard deviation were computed and analyzed for four AE parameters i.e.peak amplitude, energy, ringdown counts, and event duration. They concluded that energy changed more than event duration ,counts or peak amplitude did from their typical values for a single filament break in the bundle.

The question of viability for peak amplitude to identify source mechanisms in composites has not been unequivocally answered . To date it has not been possible to physically verify the mechanism of each AE event and then compare the peak amplitude obtained [12]. Several researchers have pointed out the potential difficulties with source identification by amplitude distribution. Henneke [13] pointed out that large signal propagation losses made it difficult to use peak amplitude alone to determine the criticality of AE source in composites . Guild et al. [14] pointed that energy released depends on both the failure mechanism and the mode of deformation applied. They also pointed out that distribution taken from tests of 0° and 90° specimens did not behave as expected if it was assumed that fiber failures have the highest amplitude . Graham [15] presented the idea that , due to statistical variation within classes of AE sources there are overlaps in amplitude such that it is difficult to uniquely define the source mechanism for each AE event based

on peak amplitude alone

Philips and Harris [16] on the basis of amplitude distribution obtained from several types of glass laminates concluded that the AE source mechanisms can't be determined on the basis of amplitude distribution alone .

Shahrokh Ghaffari et al. [17,18] analyzed event amplitude ,energy, ringdown count and rise time to identify the failure mechanism in impact test [17] and fatigue loading [18] of notched unidirectional graphite epoxy composite . Their results are depicted in the form of three dimensional histograms and point plots .They conclude that most events were of lower and middle range intensities and relatively few of higher intensity . Also a significant amount of emission is generated by friction among newly created fracture surfaces.

Megumu suzuki et al. [19] investigated on carbon fiber reinforced plastic unidirectional laminates by frequency analysis. They used frequency analysis as they thought that such AE parameters as AE count , AE amplitude and so on cannot define clearly the damage mechanism . They found that 80 khz corresponds to matrix fracture , 160 khz to fiber debonding, 270 khz to the friction between fiber and matrix and 390 khz to the fiber breakage respectively .

Graham [20] and Elsley et al. [21] used AE to analyze the signature of graphite epoxy composite specimens and made empirical observation relating to frequency content and amplitude distribution. Statistical evaluation, multiparameter co-relation, pattern recognition technique were than used to identify distinct type of AE events. However the work emphasizes that AE data,

amplitude distribution and spectral type distribution are related to fracture mechanics and further progress is to be made by the precise identification of the fracture processes .

Mittelman and Roman [22] used peak amplitude distribution to characterize damage process in unidirectional kevlar composites . They analyzed the failure mode by computing the statistical mean , standard deviation, variance, skewness and kurtosis of the peak amplitude measure using different fiber volume fraction .Averaging out the skewness for different samples they concluded that skewness values of 0.43 ± 0.16 corresponds to fiber failure and 0.9 ± 0.169 corresponds to matrix fracture specimen.

From the summary of literature survey it can be inferred that various investigators have approached the damage characterization in composites through statistical methods at first place . They then used the results for further in-depth study to categories the failure modes in the most discrete manner.

1.3 PRESENT WORK :

The present work is an attempt to develop a comprehensive procedure for acquisition of AE data and analysis of its signature through statistical method , cluster plot and histogram displays. AE data of test is recorded by interfacing the AET NorthStar Advantage 5000 to MTS-810 system . AE data recorded on AET processor is postprocessed through special software developed for specific interpretation and analysis.

Application of AE to composites must confirm to known

physics relating to AE testing . Thus the principles of AE for application to composite materials and related AE systems to be known are described in chapter 2 .

The experimental procedure and data acquisition is described in chapter 3. The present work relates to analysis of kevlar fabric reinforced epoxy resin laminates .Laminates of $[0_{12}]$,$[90_{12}]$,$[45_{12}]$, $[0_3/90_3]_s$ and $[90_3/0_3]_s$ configuration and plates made of pure epoxy, fiber rich and resin rich laminates were tested for AE signature .

AE test data from samples are in the order of thousand events per test and hence require special computational tool .The details of special software developed for postprocessing and transfer of AE data to MS/DOS system is described in chapter 4 .

The results using software developed in chapter 4 are discussed in chapter 5.

Projecting the highlights of the current investigation, conclusions drawn and scope for future work are indicated in chapter 6.

CHAPTER 2

PRINCIPLES OF ACOUSTIC EMISSION FOR APPLICATION TO COMPOSITE MATERIALS

2.1 INTRODUCTION :

Technical principles which must be adhered to in order to do a sound AE test on a composite sample are presented in this section. The organization of this section will be to first define AE and its characteristic features ; physical entities involved in an AE composite material test ; AE wave propagation ; then AE system will be discussed.

2.2 THE BASIC SOURCE OF AE :

An acoustic emission (AE event) is a complicated stress wave which is generated at a location in a structure by a rapid change in the local stress state. Mathematically this can be expressed as

$$\Delta \sigma_{ij} \; (\underline{x} \; , \Delta t \; , \Delta v)$$

Where $\Delta\sigma_{ij}$ is the change in each stress component necessary to describe the stress state at that point in the structure , $\underline{x}$ is a vector describing the location at which the rapid change in stress state occurs , Δt is the time interval over which the stress change occurs and Δv the volume (or area) of the structure which experiences the stress change.

The complexity of stress wave propagation in composites as well as its heterogeneity limit measurement of a real AE event and then calculate the source function. Hence, AE as a nondestructive evaluation technique (NDE) for composites is at present, primarily a comparison technique.

Sources of AE in composites are :

1. Externally applied load or residual stress.
2. A local micro or macro damage or deformation mechanism.
3. Stress wave generated by the local change in stress state.
4. AE generated as a response to stress and time.

These various sources can give rise to different damage mechanisms in composites like matrix cracking, fiber-matrix debonding, fiber breaks, fiber pullout and delamination. A typical damage mechanism is shown in fig 2.1.

2.3 AE SIGNAL AND ITS CHARACTERISTICS :

Classically, an AE signal from a single event (Fig. 2.2) has an exponential increase followed by an exponential decay. From the point of view of AE equipment, the definition of an AE event depends on the analog voltage exceeding a pre-set or floating voltage threshold. When the voltage exceeds the threshold an AE event is said to have been sensed. Typical AE equipment can characterize the AE event in several ways :

1. The peak voltage of the AE event.
2. The duration of the AE event (i.e. the time that the signal is above the threshold).
3. The rise time of the AE event (i.e., the time from the first threshold crossing to the peak voltage).
4. The time of arrival of the AE event (i.e., the time of day at which the first threshold crossing occurred relative to the time at which another AE event occurred).
5. The energy in the AE event during the duration ; and
6. The number of counts of the event (i.e.,the number of positive

threshold crossings during the event).

When AE is thus characterized by discrete AE events, then it is called burst type AE.

There is a second classical type of AE signal. This is called continuous AE. Continuous AE is distinguished from burst type AE by the fact that there are so many events occurring over such a short time period that the AE events superimpose on each other in time such that it is no longer possible to distinguish discrete AE events . Often , the AE observed in composites can be a combination of both burst type AE and continuous type AE. This type of AE requires a careful selection of AE equipment parameters such as threshold and dead time to obtain meaningful results.

2.4 AE WAVE PROPAGATION ASPECT :

The stress wave generated by each AE event propagate through the composite and any other possible paths to the transducer. This propagation greatly influences the resulting electrical signal out of the transducer. Aspects of stress-wave propagation that significantly influence the electrical signals are geometric spreading of the stress wave, losses due to material absorption of the stress-wave energy, direct and reflected paths from the AE source to the transducer, different modes and speeds of propagation of the stress wave.

Considering the above wave propagation aspects it is important to adopt an in-situ calibration technique. Such a technique will allow for checking the following :

1. Propagation characteristics of the test specimen and associated test fixturing.

2. The efficiency of the AE couplant.

3. The sensitivity of the AE sensor.

4. The operation of the preamplifier and other AE equipment.

The in situ calibration test is important to perform because in case of a discrepancy with the AE test,it is not possible to repeat it,since most AE generated is irreversible.

2.5 ADVANTAGES AND DISADVANTAGES OF AE TESTING :

ADVANTAGES :

1. High sensitivity (crack growth upto 2.5×10^{-5} mm can be detected.
2. Real time evaluation.
3. Total specimen volume sensitivity.
4. Clear location of damage regions.
5. Sensitivity to any process or mechanism that generate stress waves.
6. Pattern recognition aids interpretation.

DISADVANTAGES :

1. Material behaviour must be understood.
2. Quantitative correlation is limited.
3. Difficulty in discriminating between noise and signal.
4. Requires experience

2.6 AE SYSTEM :

A morphology of AE signal ,from generation of AE to final decision analysis is given in Fig. 2.3. The AE testing necessitates conversion of AE to electrical signal, its amplification, filtration, processing and recording. This forms

the raw data acquisition. Post processing of this data and applying relevant decision criteria leads to corrective judgment and action.

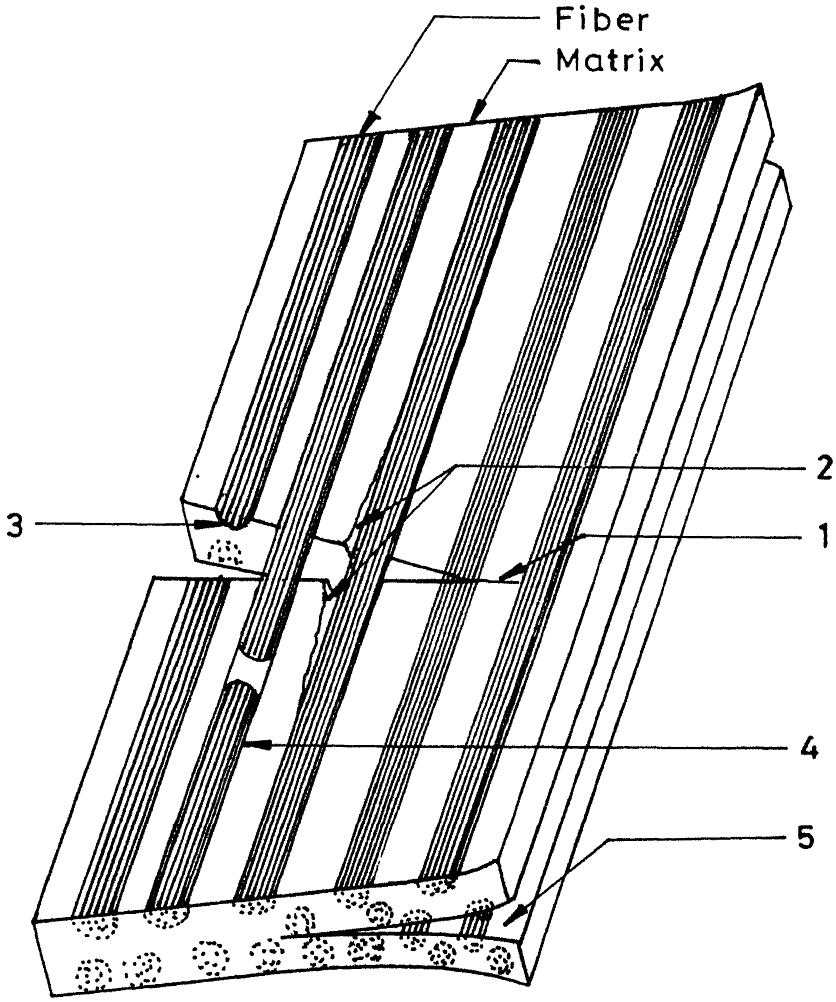
In relation to the test equipment AET 5000 used in the current analysis the system modules are as shown in Fig.2.4. Detection of AE is accomplished by the sensor acting through a couplant . The piezoelectric sensors are attached to the surface through a couplant SC6. The electrical signal from the sensors is preamplified through a high gain preamplifier of 60 db (fixed). This high gain is used because composites often have relatively high amplitudes of AE signals compared to metals. A band pass filter provided with the preamplifier results in limiting signal propagation losses. The amplified AE signal is compared to an internally generated reference voltage (the "threshold"). The comparator (or signal processing unit ,SPU) emits a pulse each time the AE signal rises above the reference voltage. Each pulse from the comparator represents a ringdown count. The SPU outputs the digital AE signal to the AE modules (the ARM, REM, TDM). It also Provides the signal to the PRM-1 (parametric / RMS module).

The ARM (amplitude /rise time module) receives the AE signal directly from the preamplifier output. This signal undergoes logarithmic amplification, and is converted to a voltage representing db. The rise time clock registers the time from first threshold crossing to occurrence of peak amplitude. The severity of source can be measured by acoustic emission intensity. The measure of acoustic emission intensities are ringdown counts and event duration as determined by the REM (ring

down counter /event duration module), energy and slope as derived from data of peakamplitude, event duration and rise time, analog parameters /rms voltage levels as digitized with reference to system power supply voltage. The analog parameters may be representative of specific parameters like load, displacement, pressure etc. The signal is then processed by the AET 5000 system and data recorded on the NorthStar advantage intelligent terminal.

NorthStar advantage is a user interactive terminal for the AET 5000. By running the AET programme AET.com, AET 5000 causes NorthStar to emulate a tektronix graphic terminal. In addition to graphic capability, AET.com also stores Acoustic Emission test data, plays it back for processing the AET 5000.

Information from the AET 5000 is collected on a disk. The I/O controller provides the necessary RS232 - C serial interfacing between the CA 4/10 computer which works on CP/M (control program for microprocessors) system and graphic display terminal (GT). The GT has a CRT terminal with both text and graphic memories .The GT data displays can be hardcopied on the Epson FX-80 dot matrix printer connected to the GT through a composite video interface .



1 Matrix Cracking
2 Fiber - Matrix Debonding
3 Fiber Break
4 Fiber Pull out
5 Delamination

Fig. 2.1 Sources of AE in fiber reinforced composites

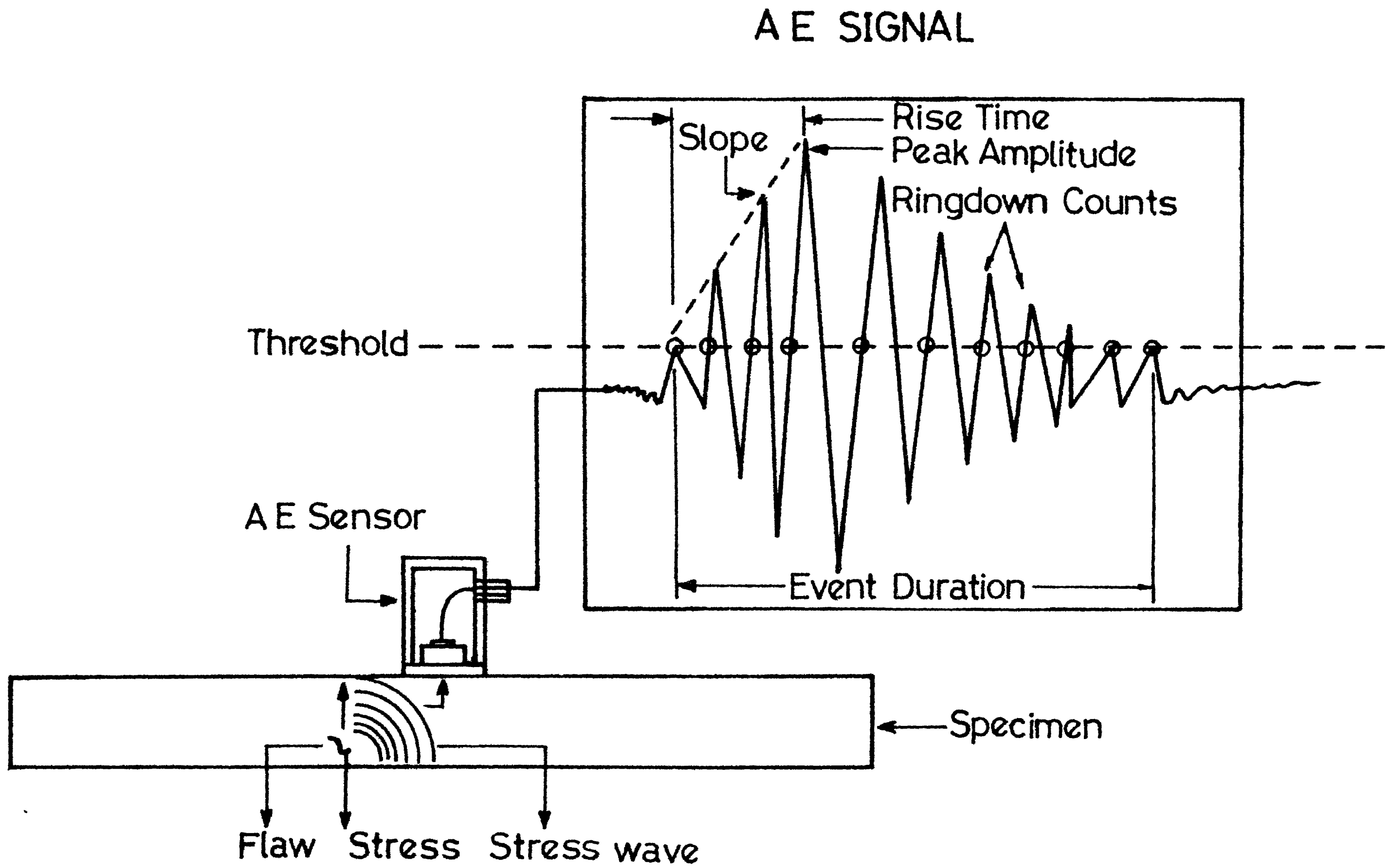


Fig. 2.2 AE Signal Generation

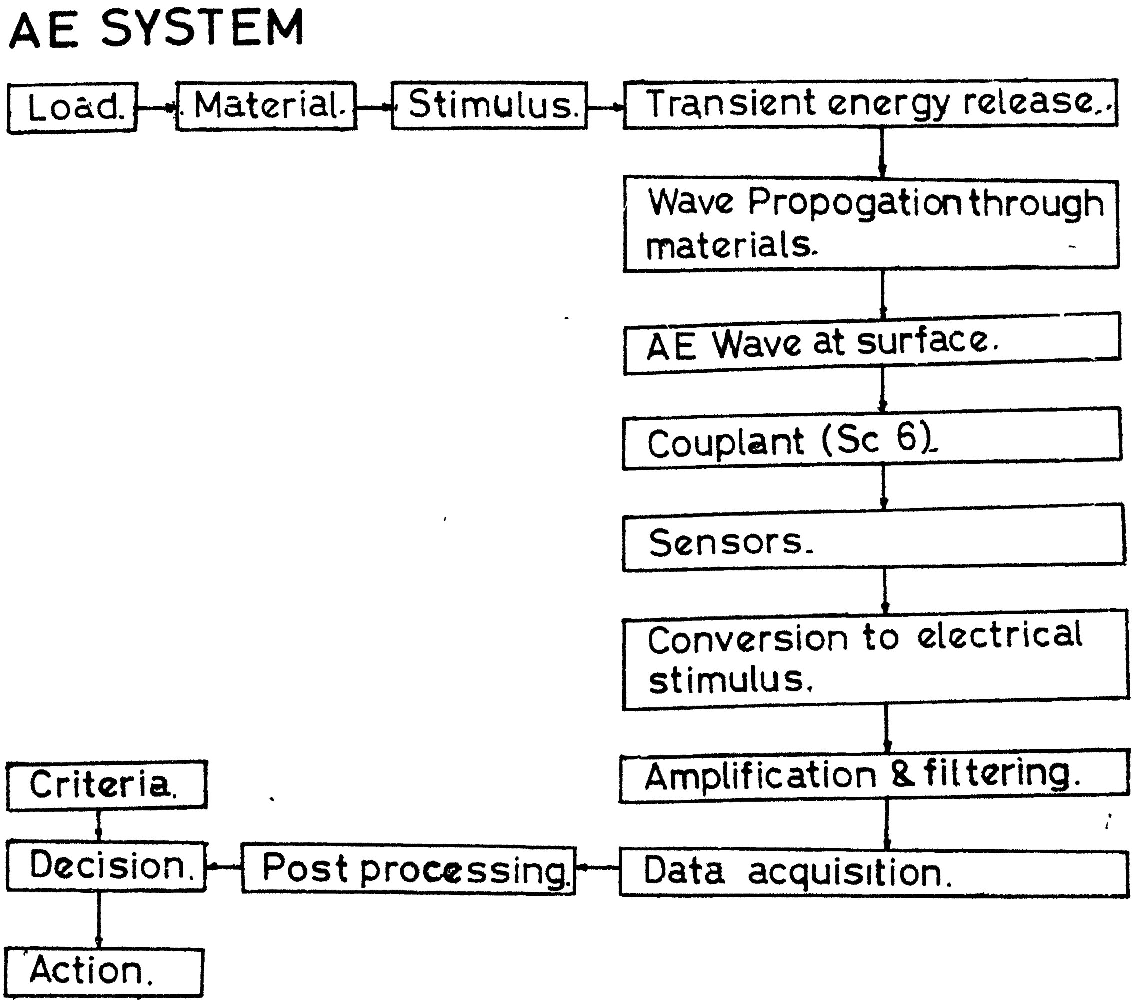


Fig. 2.3 AE System sequence

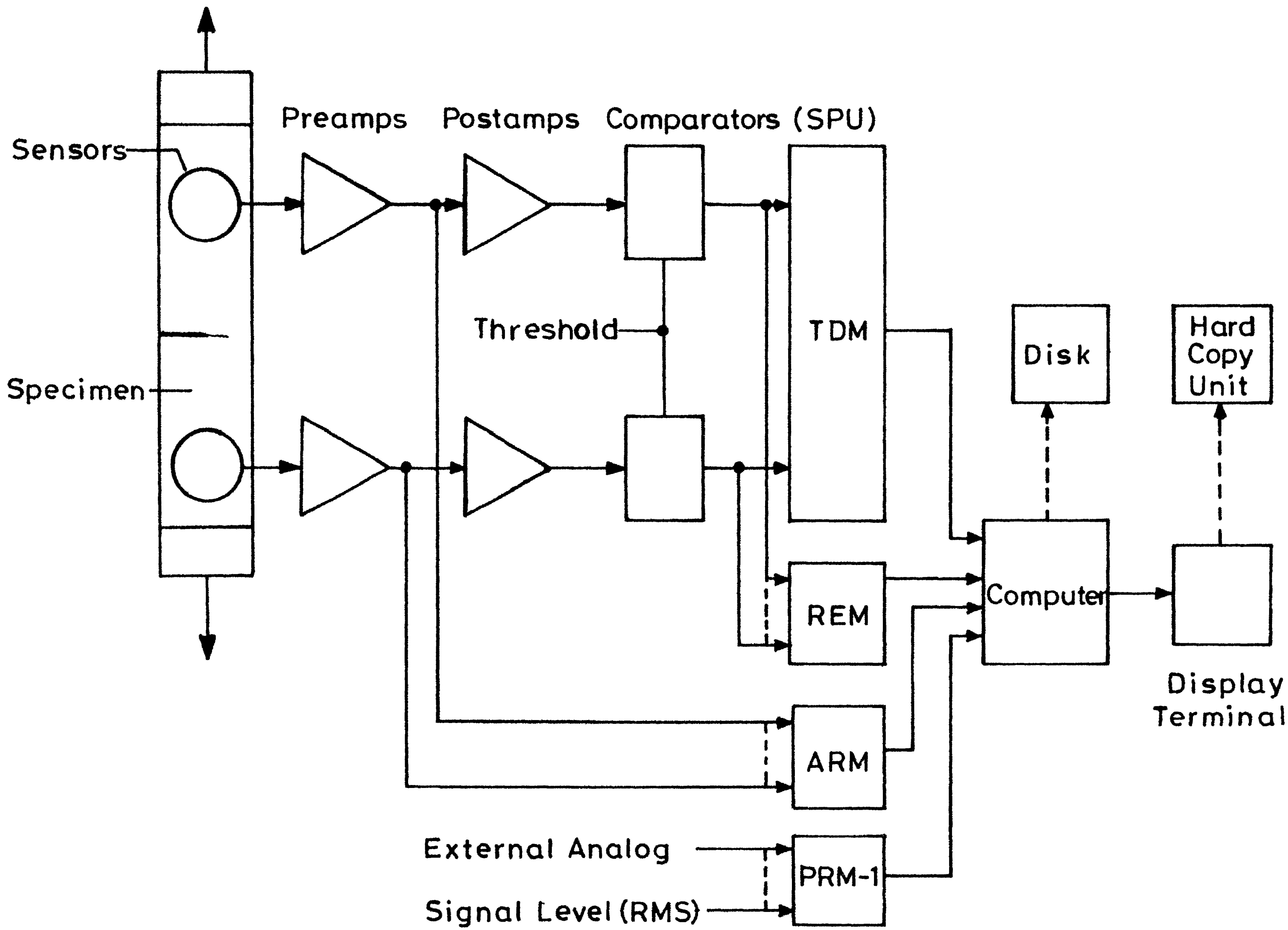


Fig. 2.4 Block diagram of a general acoustic emission system.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION :

The present investigations have been performed on Kevlar-49 fiber reinforced epoxy resin laminates of different configuration. To analyze AE characteristic of composite constituent material, investigations have been made on pure epoxy laminate, and fiber rich laminates.

3.2 MATERIALS USED :

Kevlar-49 fabric and epoxy resin were used as the basic raw materials. The specification of Kevlar-49 and epoxy resin, as supplied by the manufacturers, are given in Table 3.1 and 3.2 respectively. The Kevlar fabric used has unequal counts and denier in cross directions. This makes the fiber volume ratio in wrap and fill direction as 10:1 which is generally referred to as unidirectional weave. The properties calculated and fiber orientation angle mentioned in the present study, refer to the warp direction which is the dense fiber direction. The fabric used was pretreated by the manufacturer with a coupling agent for proper adhension to epoxy.

3.3 MATERIAL FABRICATION :

3.3.1 COMPOSITE LAMINATE FABRICATION :

Composite laminate plates were cast by hand lay-up technique. Twelve layers of fabric was cut to proper size by a special pair of scissors intended for kevlar cutting. The fabric was demoisturised by heating it in an oven at 105°C for 16 hrs.and cooled in the oven itself to avoid any moisture regain prior to processing. About 450 gms of epoxy resin (araldite LY556

was preheated to about 100°C and the temperature maintained

TABLE 3.1 : KEVLAR-49 FABRIC SPECIFICATIONS

Product		Du Pont Co., USA
C. S. Style		343
Former Du Pont Style		143
Weight (per unit area of fabric)		190 g/m^2
Tensile Strength	Warp	255700 N/m
	Fill	28700 N/m
Count (number of yarn per inch in warp x fill)		100 x 20
Yarn Denier (weight in grams of 30,000 feet long yarn).	warp	380
	fill	195
Weave		Crowfoot
Finish		CS - 805
Fiber properties :	Specific Gravity	1.44
	Decomposition temperature	500°C

TABLE 3.2 : EPOXY SPECIFICATION

Product		CIBA Geigy India Ltd.
Category :	Resin	Araldite LY556
	Hardener	Hardener HY951 (10% of Araldite by weight)
Viscosity		5000 - 8000 cp
Pot life		30 minutes to 1 hr.
Specific Gravity		1.2 - 1.3
Tensile Strength		55 - 130 Mpa
Tensile Modulus		2800 - 4200 Mpa
poisson's Ratio		0.2 - 0.33
Flexural Strength		125 MPa
Decomposition Temperature		270 - 280 °C

for 2 Hrs. to remove absorbed moisture. The resin was then allowed to cool to room temperature.

Composite plates were cast by hand lay-up between two 25 mm thick M.S. plates. The plates were nickel coated at the top and affixed with heating element at the bottom. A mylar sheet was placed on the lower mould plate. The resin and hardner were thoroughly mixed. A layer of resin was spread over the mylar sheet and the first Kevlar fabric was placed. Epoxy was applied over the fabric. This process was repeated till all the twelve layers of fibers were placed. To ensure proper fiber impregnation an aluminum roller was applied after the third layer. Another mylar sheet was placed over the top most layer. Steel spacers of 3 mm thickness were placed at all four corners between the two mylar sheets. A rubber roller was rolled over the top sheet to squeeze out excess epoxy and entrapped air. The upper mould plate was than placed in position. The mould plates were connected by uniform tightening of nuts on the bolts, provided at the four corners. Fig. 3.3 shows the entire set up .

The laminate thus prepared were cured for 6 hours at room temperature followed by 16 hours curing at 55 - 60^{o}C. After curing, the composite plate along with mylar sheet was removed. The mylar sheets were then removed to get a fine finished composite plate .

The above technique was used in making laminate of configuration $[0_{12}]$, $[45_{12}]$, $[90_{12}]$, $[0_3 / 90_3]_s$ and $[90_3 / 0_3]_s$. Volume fraction of fibers in the laminate can be calculated using the following formula (since Kevlar fibers defy the

standard resin burn-off test) :

$$V_f = (AN \times \rho_{fa} / \rho_f) / (A \times t) = (N \times \rho_{fa}) / t \rho_f$$

where

v_f	:	Fiber Volume Fraction
A	:	Area of the composite Laminates
N	:	Number of fabric layers in the laminate
ρ_{fa}	:	Areal Density of the fabric
ρ_f	:	Density of fiber
t	:	Thickness of the laminate

In the present case we have ,

$N = 12$

$\rho_{fa} = 0.190\ kg/m^2$

$\rho_f = 1.44 \times 10^{-3}\ kg/m^3$

$t = 3 \times 10^{-3}\ m$

Hence,

$v_f = 0.52777$ (52.8%)

3.3.2 EPOXY RESIN PLATE :

Epoxy resin plate were cast using prespex moulds consisting of two prespex plates (250 x 150 x 8 mms). 3 mm thick rubber lining of rectangular shape and two mylar sheets were placed between the prespex plates. The two plates were connected through bolt and nuts .

The inner surface and rubber lining were cleaned using acetone and polished using waxpol . The plates were then bolted to form the mould cavity . 200 gms of araldite LY556 was preheated in the oven for 2 hrs. and then cooled externally to room temperature. The hardener (HY951, 10% by weight of araldite) was thoroughly mixed. To remove all air bubbles the mixture was

degassed in a vacuum chamber for about 5 minutes . The epoxy thus prepared was poured into the mould. The complete mould was cured at room temperature for 24 hours. The plates thus obtained showed no voids or surface cracks on a visual inspection. The set up is shown in Fig. 3.4 .

3.3.3 EPOXY RICH LAMINATE :

These laminates were prepared similar to epoxy resin laminate except that two fabric layers were placed in-between the two 3 mm thick rubber linings, used to form the mould cavity. The cloth layers were so placed that the center region of the laminate is pure epoxy. A typical specimen is shown in Fig.3.5. These specimens were prepared because initial testing of pure epoxy specimens did not give much AE events. The fiber layer was used to aid in the AE transmission.

3.3.4 FIBER RICH SPECIMENS :

Twelve layers of kevlar cloth fabric of size (30 x 25 mm was weighed after demoisturization in the oven for 16 Hrs. Epoxy (ten percent by weight of fiber) was prepared. The laminate was then prepared exactly as in hand lay-up technique. These laminates were prepared to find AE characteristics of fiber. The small percentage of epoxy used in the laminate preparation was to just bind the layers so that, signal transmission is possible. The thickness of laminate plate thus obtained was 1.5+ 0.01 mm. The volume fraction of fibers were 80 to 85%.

3.4 SPECIMEN PREPARATION :

3.4.1 COMPOSITE SPECIMEN AND FIBER RICH SPECIMENS :

Specimen preparation involves cutting the specimens of desired size from the laminates , finishing of specimens and cutting the notches in these specimens.

Specimens of the dimensions, as shown in Fig. 3.6 were cut from the fabricated laminates. The difficulties in mechanical cutting of Kevlar composites are due to the fiber toughness. Because of its high toughness and strength, the fibers break and pull out from inside of the composite instead of cutting at the edge. This problem is more at low cutting speeds. Cutting by router at high speeds produce a lot of brooming at the edge whereas use of low power laser beam burns off the edges .

The best results in cutting laminates were obtained in circular sawing when unconventional side (slant side of teeth) of a metal slitting fine teethed H.S.S cutter was used at high speeds. Cutter size was 6 in. dia. , 2 mm. thickness with 7-8 teeth per inch. The circumferential speed of the cutter was about 30 m/s . Water was used as coolant. With this setup, cutting speed in the dense fiber direction (cutting less fibers) was quite high and in cross direction it was moderate . Brooming was very little except in crossply laminate at the edge , on the side from which the cutter comes out after cutting. The broomed fibers were removed by a special pair of scissors and the edge was finished by using water proof emery paper . During finishing operation it was ensured that the final dimensions of the specimen are as per the requirements .

The specimens were then marked and single edge notches

were cut in these. Notch cutting was done on a lathe using 0.5 mm. thick slit cutter and the a/w ratio (notch length to specimen width ratio) was kept at 0.6. All the three operations ,cutting, finishing and notch making were done with due care and the coolant was used in each of these operations to ensure a proper finish .

3.4.2 EPOXY SPECIMEN AND EPOXY RICH SPECIMENS :

The epoxy plate after casting and curing was removed and kept at room temperature for a day on a flat surface .Specimens were cut from the plate on a all cut machine with the traverse speed of cutting hacksaw at 2 mm / sec. Coolant was periodically applied .The edges were then smooth finished to get the specimens. A single edge notch of 4mm. depth was cut at the center to create a crack zone. The procedure for cutting notches were similar to the composite specimens. The finished dimensions were 210(l) x 25 (w) x 3(t) mm. and 250(l) x 25(w) x 6(t)mm. for epoxy resin and resin rich specimens respectively.

Due to the brittle failure of the epoxy specimen and low event rate the fiber cloth was interposed. The threshold was decreased to 0.5V (fixed). To supress external noise bakelite end tabs were used. This value of threshold was set after testing the noise level generated in the system surrounding.

3.5 MECHANICAL PROPERTIES :

The unnotched specimens of $[0_{12}]$,$[90_{12}]$ and $[45_{12}]$ were first tested on a 10 tonne MTS model-810 system. The material properties obtained are given in Table 3.7. The notched specimens were then tested by interfacing the AET system and MTS -810 .

TABLE 3.7 : ELASTIC CONSTANTS OF THE MATERIAL

longitudinal Modulus (E_L),	-	49.08 Gpa
Transverse Modulus (E_T),	-	12.88 Gpa
Inplane Shear Modulus (G_{LT}),	-	2.65 Gpa
Major poisson's Ratio (νLT),	-	0.193
Minor Poisson's Ratio (νTL),	-	0.051

NOTE : All properties are for the dense fiber direction .

3.6 PRELIMINARY SETTING ON AET-5000 SYSTEM :

During the performance of AE tests various settings were fed through keyboard entries as listed below .

The distance between the two sensors, used in these tests, was divided into 100 segments for the purpose of monitoring the line location. These segments correspond to locations "0" through "100" between the sensors.

The preamplifier gain for both the sensors were set to a value of 60 dB (since the preamplifiers used with each of the sensors have a gain equal to this value). The threshold level was set at a value of 1 volt fixed for composite specimens and 0.5 volt fixed for epoxy specimens .The machine noise through grips and the other noise level was observed to be less than this value after mounting the specimen. Type of tests conducted was linear, with sensor numbers 1 and 2 having locations of "0" and "100" respectively. Maximum DT was initially set as 0. This gets automatically corrected to a value obtained during the course of calibration .

Clock period of event duration module was set as 125 ns and that of rise time module as 250 ns.

Ranges of different AE parameters were set to default values itself during test .However considering triggering and white noise effect the default values for analysis were slightly modified. These ranges were used as a basis for the discrimination of selected and rejected events. The range values for test and analysis is as shown in Table 3.8.

TABLE 3.8 : DISCRIMINATION RANGES OF VARIOUS AE PARAMETERS

	MIN	MAX (Test)	MAX (Analysis)
Event Duration (μsec)	0	65520	65520
Ring Down counts	0	4096	4095
Rise Time (μsec)	0	65520	65520
Peak Amplitude (db)	0	117	77
Slope	0	65520	65520
Energy	0	165	165
Analog Parameters (# 1/2/3)	0	10240	10230

3.7 EXPERIMENTAL PROCEDURE :

The specimen surface was cleaned with acetone and made dirt-free. Two sensors were then attached to the specimen surface with their centers 10 cms. apart and equidistant from the central notch. The sensors were attached with the help of couplant, SC6 silicon grease smeared on the shoe of the sensors in a light layer. A special 'C' clamp was used to ensure intimate contact between the sensor shoe and the specimen.

Firstly the calibration of the test was performed with each specimen to get a representative speed of sound in the specimen

material. The calibration is to be done in case of every distinct specimen configuration since the specimen geometry has an influence on the result. Calibration was performed by placing a standard AE source, in terms of another sensor which is connected to the mainframe's 5 volts output pulse, at a small distance from one sensor , outside the 100 segment region . The standard AE source simulator sends out a signal of constant level. A constant output is more important than the actual level. The difference in arrival time (DT) of this signal at the two sensors was used by the system computer to determine the representative speed of sound in the material .

The pulser was then detached and the specimen was mounted on MTS machine. Mounting was done in load controlled mode. Hydraulically operated grips of the machine help in the speedy insertion and removal process of the specimen in addition to providing excellent axial and angular alignment. The MTS load and stroke digital indicators were set at a positive value of about 0.02 volts. This was done to avoid any overflow. The AET was then completely interfaced to MTS- 810 system by connecting the analog parameter probes in the specific sequence. Load and displacements were recorded on AET-5000 system as external analog parameter 1 and 2 .

The various test parameters were :

Load 10% (1000 kgs) i.e. 10 volts = 1000 kgs

Stroke 10% (10 mm) i.e. 10 volts = 10 mm

Specimen length between grips = 15 cms.

Time for test : 10 minutes in stroke controlled mode.

The tests were conducted in stroke controlled mode so

that the load displacement behaviour beyond maximum load is also clearly indicated. Data recording on AET computer was initialized by system commands and by opening a file for data collection The AE system computer and MTS 'RUN' were operated simultaneously to begin the test. Tensile test was performed upto fracture. The end of test was done by closing the data file properly and issuing a 'END RUN' command. Figure 3.9 shows the overall view of the specimen under test on MTS and AET 5000 monitoring system. Figure 3.10 shows the damage zone in the laminates of different configuration.

Postprocessing of recorded AE data through specially developed software is explained in the next chapter.

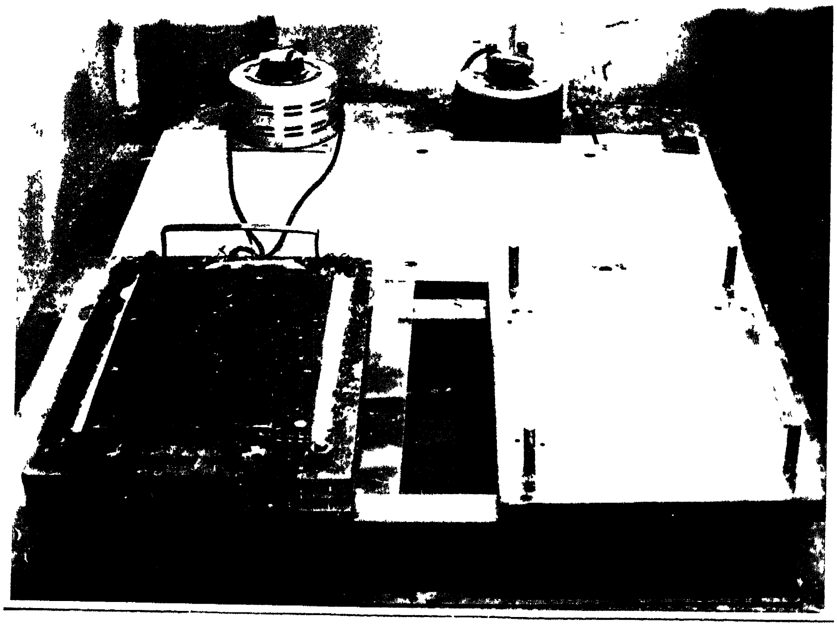
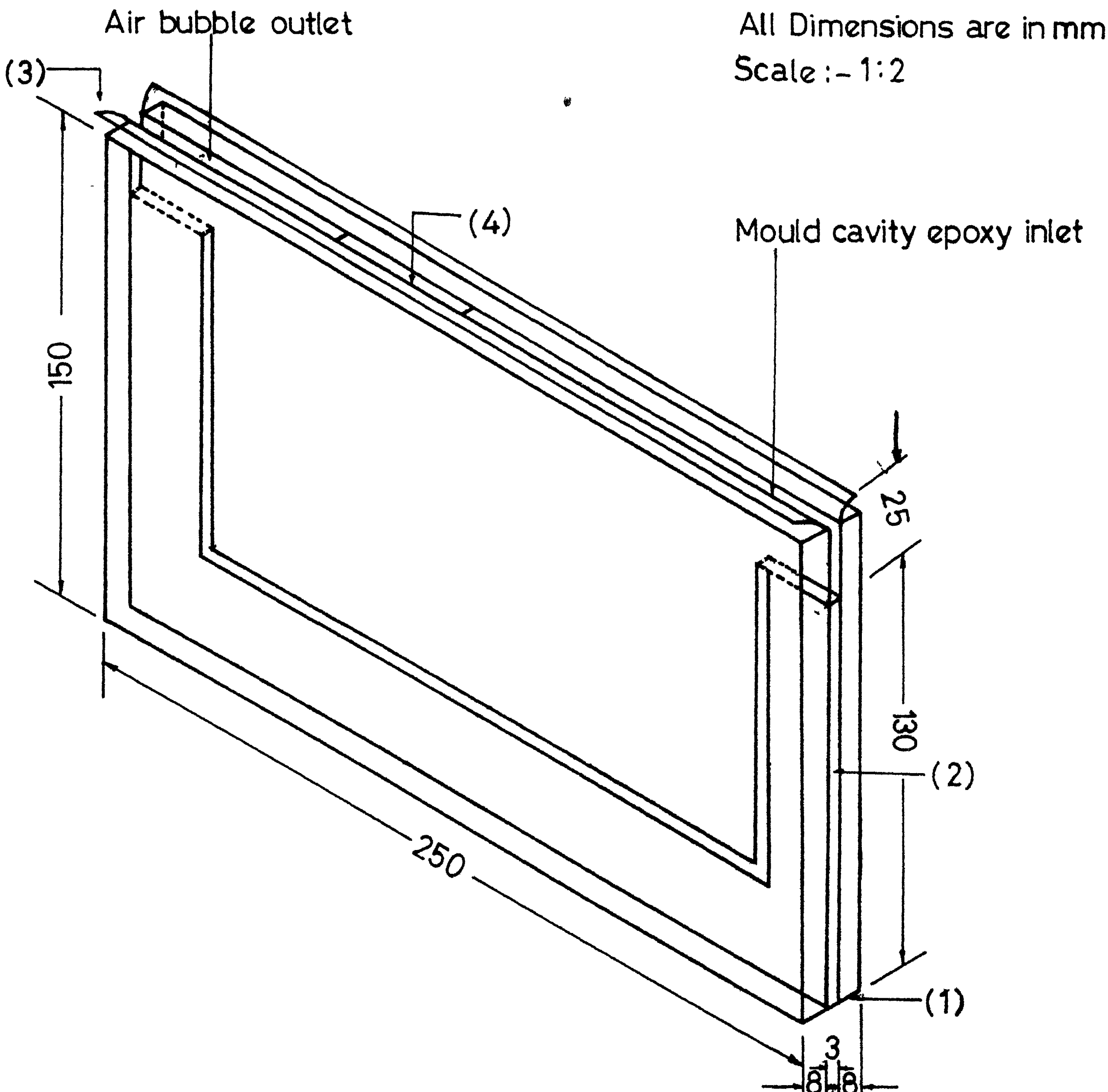


Fig. 3.3 Composite laminate fabrication setup.



(1) Perspex Plate (250 x 8 x 150), 2 nos
(2) Rubber Lining (250 x 3 x 130 x 25)
(3) Mylar Lining
(4) Spacer

Fig. 3.4 Epoxy Resin plate moulding unit

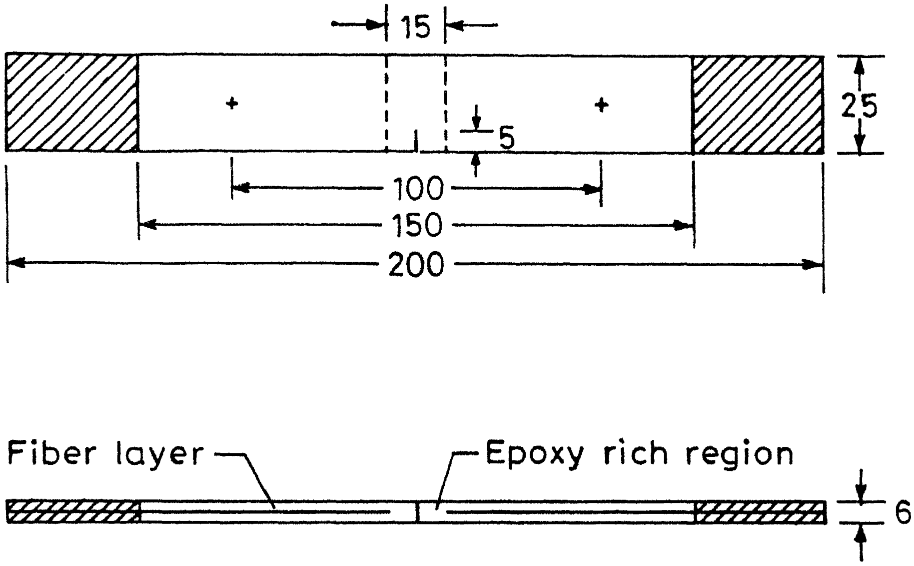
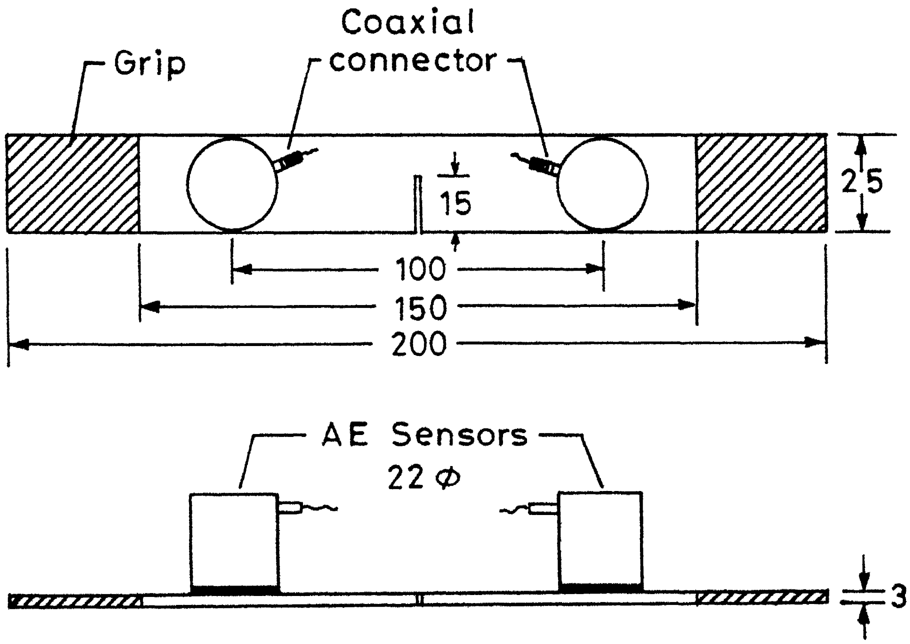


Fig. 3.5 Epoxy rich specimen



All dimensions in mm

Fig. 3.6 Composite specimen geometry

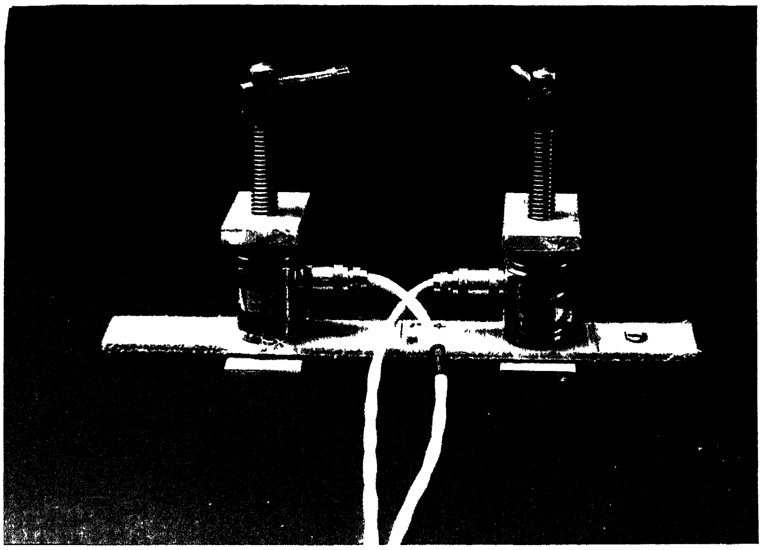


Fig. 3.8 Typical sample with AE Sensors.

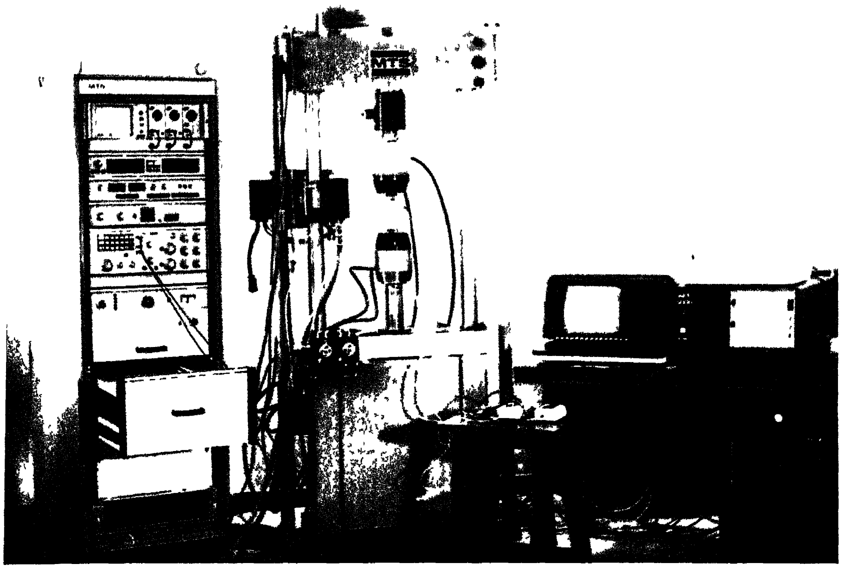


Fig. 3.9 An overall view of AE system with specimen under test on MTS .

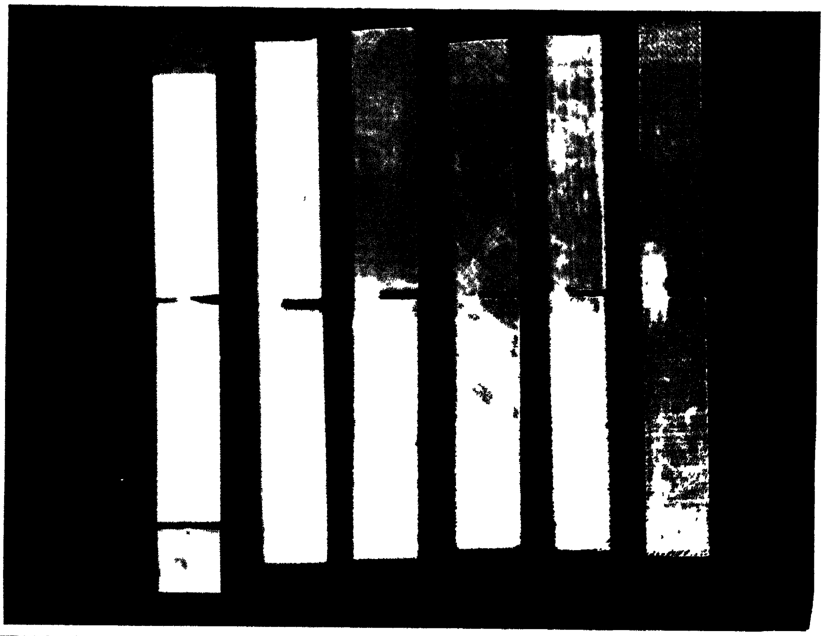


Fig. 3.10 Damage zone :

(a) $[0_{12}]$ sample

(b) $[90_{12}]$ sample

(c) $[45_{12}]$ sample

(d) $[0_3/90_3]_s$ sample

(e) $[90_3/0_3]_s$ sample

(f) Epoxy specimen

CHAPTER 4

SOFTWARE DEVELOPMENT

4.1 INTRODUCTION :

AE data recorded during a test can be best utilized when procedures for analysis are appropriately developed. The AET system and 8-bit Northstar Advantage graphic terminal has real time graphic capability for the purpose of data recording and analysis in real time. Real time histogram displays can be set during the test. However these displays are not for specific application. Setting of real time display results in loss of some of the unprocessed events, since the processor discards the data during the periods when the buffer memory is full.

A postprocessing program "POSTPRO" capable of listing event output, crossplots and histogram displays of recorded AE data was supplied by system manufacturers. This program could not be effectively utilized due to an error in declaration of some array. The program being machine coded could not be rectified .

Another software "USERPRO" is a 'Skeleton program' provided by AET, for event listing. It allows the user to write any CBASIC (A advanced version of BASIC) program for specific data analysis purpose. The description of AET 5000 data file format, method of data retrieval by the use of this code and the detailed description of this code are contained in reference (23).

AE data obtained from testing of composite laminates are random in nature . Composites due to their heterogeneity gives rise to several microfracture processes during flaw growth. The aim of this study was to analyze such random data and

correlate the event occurrence with different type of failure modes associated with composites. The best way to quantify a random data is the statistical method. Hence for our specific requirements of data recording and analysis, new softwares had to be developed .

4.2 SOFTWARE DESCRIPTION :

To analyze the signature of composite specimens by statistical means a software "STATPRO" was developed . In order to classify the data into different category and study the statistical variation two other softwares coded "CROSSPO" and "HISTPRO" were also developed. All these softwares were developed with the AET supplied skeleton program "USERPRO" as the framework. The detailed description of the softwares are given below.

4.2.1 COMMON FEATURES :

The common features in all the developed softwares are:

1. User interactive with graphic capability.
2. Applicable for any AE testing be it fiber composite, pressure vessel, metal matrix composites etc.
3. Wide flexibility in listing of output and plots at users discretion.
4. Simple inputs through prompts from system.

4.2.2 'STATPRO' PROGRAM :

An AE event is characterized by real time parameters like ringdown counts (RDC), Event Duration (ED), Rise Time (RT) and Peak Amplitude (PA) . Other derived parameters are Energy,

Slope and Location In order to classify from a random set of data through statistical analysis four AE real time parameters i.e. RDC, RT, PA, ED and one derived parameter Energy were selected. Energy was selected because some investigators had reported certain correlation between Energy and PA [6, 24, 25, 26].

The base for statistical classification were the analog parameters 1 [AP1] and analog parameter 2 [AP2] , which in the present study map to load and displacement values. As all tests conducted are in stroke control mode the parameters for classification is displacement, the measure of which is given by AP2 (in millivolts). The maximum value of AP2 recorded from the graphic plot of MTS was considered as 100% value. This value was divided into twenty equal parts each representing a five percent stroke range. For all events in the range the Statistical Mean [$\overline{X}$], Standard deviation [σ], Skewness [M] and Kurtosis [K] in the AE parameter selected was computed using the following equations [27].

$$\text{Mean } [\overline{X}] = \sum_{i=1}^{n} X_i/N$$

$$\text{Standard deviation } [\sigma]^2 = \sum_{i=1}^{n} (X_i - \overline{X})^2/N - 1$$

$$\text{Skewness } [M] = \sum_{i=1}^{n} (X_i - \overline{X})^3/\ \sigma^3 N$$

$$\text{Kurtosis } [K] = \sum_{i=1}^{n} (X_i - \overline{X})^4/\ \sigma^4 N$$

Direct computation of these values from the above formula required more storage arrays and the program had to be run twice. However , the equations were modified using the following statistical principles listed in [28].

1. The sum of a group of terms involving a constant

multiplied by a variable equals the constant times the sum of the values of the variable.

2. When a constant appears once for each expression the sum of the constants can be expressed as the product of the number of times the constant appears and the value of the constant.

The modified form of the equations are :

$$X = \sum_{i=1}^{n} X_i / N$$

$$\sigma^2 = [\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2/N] / (N - 1)$$

$$M = [\sum_{i=1}^{n} X_i^3 - 3 \sum_{i=1}^{n} X_i/N \{\sum_{i=1} X_i^2 - (\sum_{i=1}^{n} X_i)^2/N\} - (\sum_{i=1}^{n} X_i)^3/N^2] / (\sigma^3 N)$$

$$K = [\sum_{i=1}^{n} X_i^4 + \sum_{i=1}^{n} X_i/N \{6/N (\sum_{i=1}^{n} X_i \times \sum_{i=1}^{n} X_i^2) - 3 \sum_{i=1}^{n} X_i^3/N^2 - 4\sum_{i=1}^{n} X_i^3\}]/(\sigma^4 N$$

Using the above set of equations the program was framed to compute all required statistical data in a single run.

The software is very simple to operate . The primary inputs are just six values i.e. maximum value of load [MV], maximum value of stroke [MV], loading rate, displacement rate, mode of conducting the test (load/stroke control) and region number. All these inputs are known to the user from the test setting and graphic output of MTS-system. Provision exist for computation of statistical data depending on the mode of testing. In the present study all tests were conducted in stroke control mode and hence the term stroke will only be referred to.

The highlights of the software include :

1. The statistical measures are computed between 0 to 100%

stroke at every 5% range for all AE parameters selected.

2. The cumulative statistical measures from 10 to 100% stroke in steps of 5%.

3) The values of statistical measures can be taken as a hardcopy .Provision exist for two types of plotting,

   a)Any of the AE parameter vs. load/stroke percentage.

   b)Any of the statistical measure for all five AE parameters vs. load/stroke percentage.

   The above provision for plotting occurs likewise for cúmulative statistical data also.Thus in all for any one test 18 different plots (5 graphs per plot totaling to 80 graphs) can be obtained at the discretion of the user.

4) The AE data collected is properly categorized discriminating all spurious data events which occur due to triggering and white noise. Events classified as spurious data are those which have the maximum default values set by the system for any of the AE parameters. These values have been identified and discrimination levels set for [refer Table 3.6] 11 AE parameters in the program enabling correct quantification of data in the range of interest. The output is the maximum and minimum values for the 11 parameters from selected events. This output is highly useful in running other programs thereby reducing the running time to a large extent .

5) Another important output from the program is the number of AE events at different stroke levels.This data

gives significant information on the AE activity in the material and aids in the signature analysis.

The hardcopy output for any of the four results stated above is at the discretion of the user.The user needs to answer only "yes" or "no" to the questions that occur after reading and preliminary computation of all events (Only the first alphabet 'Y' or 'N' will suffice). only a few questions are present in the entire program and no more than four prompts would be present at a time on the monitor screen. Provision for taking the plots repeatedly due to any human entry error exist. Procedure for plotting will appear on the screen thus giving complete instruction to the user before plotting. The simplicity of the program operation can be well judged from the flowchart and sample dialogue placed in appendix B. Appendix A lists the flow chart index common to all softwares.

Analysis of the data from histogram and cross plots together with statistical data helps in better justification of the results. A software "USERNEW" [29] was developed to list events, generate histograms and crossplots. However this software was found to have various drawbacks. These main drawbacks include:

1) No discrimination was set and hence spurious data due to triggering & white noise present formed part of the selected events.
2) The software had to be run in two cycles because the minimum and maximum values for plotting was not known a priori.
3) Only three histogram plots could be obtained at a time with a maximum of 15 interval setting.

4) The crossplot could not be generated due to presence of spurious data.

5) Only one output listing form was available.

The above drawbacks were overcome by setting discrimination ranges and including several new features for better understanding of the data. Two optimized user interactive software thus developed are "HISTPRO" and "CROSSPRO".

4.2.3 'HISTPRO' PROGRAM :

HISTPRO Program offers representation of the data in the form of histograms. The general procedure for processing and display of histograms on the monitor is in accordance with the earlier developed software 'USERNEW'. The highlights of 'HISTPRO' software include :

1. The program needs to be run in only one cycle.
2. Nine histograms can be obtained at a time with maximum of twenty interval settings.
3. With Events as Y- axis variable, distribution of events at different stroke levels (maximum three per plot) and plot at 100% stroke can be obtained.
4. In case of plots with other than event distribution as parameter,the number of events at each bin is displayed on the monitor and this helps to change the 2D plot to a 3D plot. Also the following two plotting provision exist :

   a) Cumulative plot with reference to Y- axis variable.

   b) Average plot with reference to Y- axis variable.
5. Provision for obtaining normalized plot exist.

With the above modification the program efficiency has been increased by more than 800% compared to 'USERNEW' program.

Execution of the program is as detailed in the flowchart in Appendix C. A sample dialogue is also included. The primary input data are mode of conducting the test, and maximum value of corresponding analog parameter. The system then offers the user to select the Y and X axis variables for each display. If the Y - axis variable is distribution of events then an option exist for generating histogram plots at three different load/stroke levels apart from the 100% level. The user also specifies the test and region for plotting or the sensor number if the plots are with reference to a sensor. A maximum of nine displays can be set in a run. When the display setting is complete, the system lists on the monitor the display parameters, test # and region #. The system now prompts for the secondary inputs for each display # set. The inputs correspond to plotting details. These are minimum value of X- axis variable, no of plot intervals, size of interval, and maximum value for plotting. The calculation for the Y- axis variable can be in two forms, if Y- axis variable is not distribution of events. These are average plots and cumulative plots. In case of average plot the mean value of the entire data of each bin is calculated. In case of distribution of events being the Y axis variable the value for a particular bin is incremented by one with every event falling in that bin.

When all the events are processed and are put in bins the system prompts the user to select the display to be displayed on the monitor. Hardcopy output can be taken through a screen dump.

4.2.4 'CROSSPRO' PROGRAM :

The CROSSPRO software was intended to list the event data as per users requirement and obtain plots of any two AE parameters. The flowchart for the program and a sample dialogue is shown in appendix D. The program offers two main options. option - 1 is Listing of events and option - 2 is Crossplots.

If the first option is selected, CROSSPRO offers the user a flexibility in selection of output form. Four different form of event output can be obtained . These are :

1. List to printer both selected and rejected events.
2. List to printer only selected events.
3. List to printer only selected or selected and rejected events between any two load/stroke percentage levels.
4. List to monitor only selected or selected and rejected events.

Once the form is selected CROSSPRO reads the AE data from the specified file, available on a disk. For each of the events read from the disk , energy, slope, location, region and event time are calculated. Depending on discriminatory ranges set the events are classified as selected or rejected events. Based on the form selected the events are listed either to the printer or monitor.

If the second option is selected CROSSPRO prompts for selection of a mode for two sub-options which are:

a) Generation of normal crossplot between two AE parameters.
b) Generation of statistical based cluster plots.

Once the user specifies the sub-option as per

requirement the system prompts for specific inputs, which are the mode of conducting the test, the relevant maximum value of load/stroke, X and Y axis variable; and their corresponding maximum value, test and region #, or sensor #.

The system now offers two other options which are :

1. Crossplot of chosen parameters under chosen sub-options to be plotted from 0 to 100% load/stroke values.
2. Crossplot of chosen parameters under chosen sub-options to be plotted between any two load/stroke percentage levels.

The drawing options are next prompted for . In both cases the drawing option can be points or lines connecting successive points.

In the case of statistical based cluster plots (sub-option 'b') the AE parameter's mean [$\bar{X}$] and standard deviation [σ] values for X and Y axis variables are prompted for. The $\pm\sigma$ limits from the mean line is taken as the demarcation zones for both X and Y axis variables. Hypothetical lines drawn from the $\pm\sigma$ limits gives nine rectangular blocks. Events falling in each of these blocks are plotted using different alpha numeric characters. A counter provided for each block gives the number of events in the block at the end of plotting.

The next stage is continued after the user confirms that the settings are correct. Any change due to human entry error can be rectified by again beginning from the start. An option exist for doing this before plotting commences. Once the instruction to the program to start and the Title/Comment is given, the software clears the monitor screen. The axes are first plotted and the plot heading displayed. Events

corresponding to the concerned test or sensor and the region are plotted, on the drawn axes as these are read. Only one crossplot is possible during a run since it involves direct plotting of events, as they arrive on the screen. The end of crossplot for any option and combination selected is indicated by the display of title/comment given.

4.3 RUNNING OF THE CODE :

The extended code for the inclusion of the above mentioned features in three softwares was entered using the document mode of wordstar. The edited version was compiled using the program BASIC.COM supplied by AET. The location address of assembly language routines, used with these softwares, were changed to create sufficient memory space for the developed softwares. Since the graphic capabilities are included in the software, the NorthStar graphic manager was appended to the file RUN.COM, which is used for the execution of CBASIC programs. Appending of graphics manager was achieved using a program GMGRADD.COM.

The compiled versions of any of these softwares can be executed using the command RUN #### (#### refer to the software code e.g. STATPRO). When the data file name is asked, the disk containing the data file should be mounted and the file name with extension (e.g. SAMPLE.D01) entered through the keyboard. Since CBASIC will not read the binary files the data from the file is read with the help of an assembly language program FILEOPS. The access to the NorthStar graphics manager is provided by another assembly language routine known as GRAPHICS. GRAPHICS load

registers from a memory area set by the various graphic functions and call the graphic manager . A third assembly language program is also used known as LOADER. LOADERS's function is to read assembly language program files into memory at an address specified in each file. The Program can be halted at any time, while it is processing by typing CONTROL-C.

In the present study the accumulated AE data from various tests is postprocessed using the developed softwares. Thus all the softwares have been tested for adequate and meaningful postprocessing.

4.4 FILE TRANSFER FROM CP/M SYSTEM TO MS-DOS PC :

The present NorthStar advantage working on CP/M operating system has a 15MB Winchester and a floppy drive. Due to an error in the winchester tracks the drive could not be booted. Absence of winchester and working with a single floppy system limited our analysis capablity. With the system program, assembly language routines and graphic manager occupying 44K out of the available 64K memory, only 20K was available to the user for programming. This space is highly insufficient for writing complex programs.

Another major problem is the inherent system speed. NorthStar advantage being run on a 8 bit processor has very slow computational rate compared to a PC/XT. As an e.g. A statistical analysis of one AE test containing 4000 events takes 6 hrs. with the CP/M system , while the same if processed on a PC/XT would take only one half-hour. Due to the above disadvantages it

was very essential to transfer the data from the CP/M system after the test to an MS-DOS PC/XT for postprocessing. With the above concept the objective was to implement a file transfer facility to enable data gathered by the CP/M system to be processed on the PC for reasons of speed and efficiency. The serial port of the two systems has been used to provide a physical connection based on the RS-232C standard. A brief outline of the software on both systems is described here.

The CP/M system has a 8251 USART on its SIO board on slot 5, which is programmed for asynchronous transmission at a user designated baud rate. The program on the CP/M side has 3 modules.

(1) FCB setup : This module is used for inputting file name and creating a File Control Block for accesing and reading the file sequentially into main memory.

(2) USART initialization: This module programs the 8251 for the desired baud rate, no of bits/char etc which exactly matches the parameters with which the 8250(on the PC) has been programmed.

(3) Main loop: This is the module which actually reads the file from disk into a RAM buffer in blocks of 128 bytes. After each block has been read it is passed on to the 8251 for transmission.The protocol followed during the transfer is a standard one which makes use of three special ASCII characters for handshaking namely STX(start of text), ETX(end of text) and DLE(data link escape). No mechanism of flow control has been felt necessary at present but can be added on if the need arises to transfer large files which are too big to be buffered in the RAM of the PC.

On the PC side the software is much simpler as File access

in DOS does not require FCB creation/setup. Also the COM2 port is initialised using the **mode** command provided by DOS (Details on how to specify this command are given in DOS manual) [30], and not through the program.The main module is organised as follows.

After a destination file has been opened and a handle obtained, the 8250 is polled for an STX char. Once this is got, the remaining characters are received into a buffer until an ETX is got. All the characters between the STX and ETX are part of the data and are written into the file on disk. If either STX or ETX or DLE are part of the data they are preceded by a DLE. The char following the DLE is taken as part of the data and the DLE is discarded. Once the ETX has been received, the transfer is complete and the buffer is written onto disk. The file is now closed and the program exits.

An example of a typical transfer session is presented below.

Input :**mode COM2:12,e,7,1**

This programs COM2 for 1200 bits/sec, even parity, 7 bits/char and 1 stop bit. This mode 2 command is used to set COM2 parameters.

The program on the PC side is invoked and the file name is input in response to its prompt **File Name:** .The PC is now setup for transfer.

Similarly the transfer program on the CP/M is invoked and the file to be trasferred is input . The file transfer now proceeds in the manner described earlier.

CHAPTER 5

RESULTS AND DISCUSSIONS

Damage propagation in composites through AE technique has been studied for the following types of samples :

a) Unidirectional laminates of $[0_{12}]$, $[90_{12}]$ and $[45_{12}]$ ply configuration .

b) Crossply laminates of $[0_3/90_3]_s$ and $[90_3/0_3]_s$ ply configuration .

c) Plates of pure epoxy and fiber rich laminate.

Analysis of data has been carried out in two steps: Statistical analysis to select AE parameter influencing the damage mechanism, and classification of damage modes through statistical cluster plots and histogram displays.

5.1 SELECTION OF PARAMETERS INFLUENCING THE DAMAGE :

If an event with the four real time characteristic has to be identified with a damage mechanism, the best process is to consider the position of the event in a four dimensional space (4D space). Events of the same characteristic when positioned in this 4D space would combine to form distinct clusters, identifying for different damage mechanism [31]. Due to the impracticability of representing events in a 4D space the next best is to study the statistical variation of the four real time parameters and select the most appropriate parameters for classification. The entire statistical data was computed for each test and the results plotted using the software "STATPRO".

Figures 5.1, 5.2,and 5.3 show the statistical measure Viz. Mean, Standard deviation, Skewness and Kurtosis for the four

AE real time parameters (Peak amplitude, Event duration,Ring down count and Rise time) computed and plotted at every 5% stroke level from 0 to 100% stroke ,for [0_{12}], [45_{12}], and [90_{12}] laminates. Fig. 5.4, 5.5, and 5.6 show the cumulative statistical plots for the same laminates.

A preliminary investigation of the plots will indicate:

1) The mean and standard deviation of the AE parameters fluctuate between different intervals of stroke. This substantiate that AE activity takes place as a random process. When different mechanisms interact to cause damage, the AE event characteristics also changes. This variation implies the heterogeneous failure mechanism involved in composites .

2) The variation of kurtosis in RDC (Fig. 5.1a, 5.2a, 5.3a) and in RT (Fig. 5.1d, 5.2d, 5.3d) are found to be more erratic and leptokurtotic (Kurtosis > 3) implying the accumulation of a large number of events near the mean value. The cumulative plots (Fig. 5.4d, 5.5d, 5.6d) which normally must be linear, also shows such variation in case of RT parameter. Larger variation in skewness in these two parameters were also noticed. Due to the above abnormality it was considered that RDC and RT would not be a true representative of the damage classification.

3) The variation of statistical measures for peak amplitude in range plots (Fig. 5.1c, 5.2c, 5.3c) and cumulative plots (Fig. 5.4c, 5.5c, 5.6c) show a good uniformity. From the histogram plots (Fig.5.19 - 5.24) the variation can be considered to follow a normal distribution pattern.

4) In the case of event duration the variation of mean and standard deviation are higher in some intervals of stroke. There

is a consistency in kurtosis and lesser skewness variation (Fig 5.1b, 5.2b, 5.3b). Also the coefficient of variation computed was found to be less than that of RDC (refer Table 5.11). The cumulative plots also show a good consistency in statistical parameters (Fig.5.4b, 5.5b, 5 6b). This implied the clustering of the data within certain limits over the mean. From the above it was inferred that peak amplitude and event duration can be the best parameters for data classification.

The effectiveness of this selection was confirmed by a study of the event listing and testing high fiber volume fraction specimens.

A listing of selected events were taken from 10 to 40% 65 to 75% and 90 to 100% stroke using "CROSSPRO" program. The reason for the above percentage of stroke selection is as follows:

The interval 10 to 40% stroke represented the linear portion of load displacement curve in all cases and the general damage mechanism that occur are interface failure , fiber failure at the notch tip.

The 60 to 75% stroke in all cases were associated with the drop in load due to ply failure. The damage mechanism that appropriately occur in this range are matrix cracking, delamination and debonding.

In 90 to 100% stroke range the AE events generated are more due to the ultimate specimen failure. The ultimate failure appropriately associate with fiber fracture.

The study of event output from the above for different

samples showed a pattern ,though not very distinguishable. This gave only an insight to test more samples associated with certain predominant failure mechanisms as detailed below. Specimens with high fiber volume fraction (80- 85%) and pure epoxy samples were tested for AE characteristics The emission due to high fiber volume fraction showed that large percentage of the events had PA > 60 and ED > 100.

Testing of pure epoxy specimens posed problems due to the brittle nature of the sample. The number of AE events per specimen obtained were small . About 45 samples were tested for AE characteristics with the threshold set at 0 5 V (fixed). The data obtained from these specimens indicated that most events were of amplitude range 25 - 35 db and ED varying from 1 to 30 microseconds.

With PA and ED as the base for classification certain observations are made in unidirectional and crossply laminates.

5.1.1 UNIDIRECTIONAL LAMINATE ANALYSIS :

1. AE initiates at early stage in $[0_{12}]$ sample compared to $[90_{12}]$ and $[45_{12}]$ samples (fig. 5.1 to 5.6),
2. A sharp rise in mean is followed by a rise in standard deviation , kurtosis and skewness in most cases .
3. The skewness value for PA and ED in maximum cases are positive and less than 1.6 for $[0_{12}]$ and $[90_{12}]$ laminates, while going upto 3.5 for $[45_{12}]$ laminates. The positive values reflect on the right tail of the distribution being heavier.
4. In $[45_{12}]$ samples there were regions between two stroke percentages where the number of events selected are nil. The

software is so modeled that at such juctions a gap is left in the plot. These gaps are indicated by true horizontal lines. The reason attributable for the occurrence of nil events are, due to sudden increase in displacement, either the events are all rejected or the range of displacement is small.

5.1.2 CROSSPLY LAMINATES ANALYSIS :

The procedure adopted to study crossply laminates were same as that adopted for unidirectional laminates. As in unidirectional laminate examination of statistical variation and output listing showed a better uniformity in PA and ED compared to RDC and RT. Taking the base parameters as PA and ED certain observations made from the Figures 5.7 to 5.10 are :

1. Samples with $[0_3\ /90_3]_s$ have larger mean values and standard deviation compared to those of $[90_3/0_3]_s$, while the skewness and kurtosis values are over the same limits. This implies that more fiber related damage can be seen in $[90_3/0_3]_s$ samples.
2. The cumulative variation in PA and ED are consistent. Fig.5.9c and 5.10c show the PA variation. Fig. 5.9b and 5.10b show the ED variation. Due to the uniformity PA and ED can be considered as reference parameters for damage classification.

Certain observation could be further drawn from an in-depth study of the range plots in unidirectional and crossply samples. These include:

In most samples tested distinct variation of AE parameters with positive and negative slopes (generally > $\pm$ 50°) was observed. Also smaller slopes (< $\pm$ 40°) was observed.

A study of the event output in these regions from all

samples showed that in 80% of the cases where a steep rise exist most events had higher values of ED and PA. Where a steep fall exist most events had lower values of ED and PA. However smaller slopes, both rise and fall were found to have events in the middle ranges without offering much clarity for distinction.

One inference could be drawn from the above. In-between any two stroke values the variation of mean can give an idea on the dominant failure mechanism. It is felt that the steep rise represent the dominance of fiber failure and steep fall represent matrix related failure. The smaller slopes are due to predominance of interface failure .

In all the samples tested there was an initial rise in mean over the first 10 - 15% stroke and rise after 85% stroke. The initial high rise accompanied by large event generation can be associated with fiber failure because at the notch tip due to high stress concentration , the rupture of fibers is dominant.

Table 5.11 illustrates for different sample configuration the average total number of events and coefficient of variance. It can be seen that in all cases the coefficient of variance is less than 1.0 for PA and ED. In case of RDC and RT measures the coefficient of variance were greater than that of ED and also above 1.0 in some cases.

The value of coefficient of variation in PA for all samples reported here are about 5% greater than those reported by A. Mittelman and I. Roman [22]. The difference is attributed to the following two factors :

1. The reinforcement considered in the analysis is not truly unidirectional but of crowfoot weave.

2. The method used in this analysis for laminate fabrication is by handlay- up technique using LY556 /HY951 epoxy. Mittelmen and I.Roman used prepregs with MY750 /HY972 epoxy.

TABLE 5.11

Sample configu- ration.	Total No. of events	Coefficient of variance		
		ED	PA	RDC
$[0_{12}]$	2860	0.640+0.040	0.282+0.030	0.670+0.041
$[90_{12}]$	1420	0.670+0.131	0.236+0.040	0.740+0.030
$[45_{12}]$	2240	0.649+0.045	0.248+0.016	0.972+0.025
$[0_3/90_3]_s$	4270	0.701+0.122	0.271+0.016	0.878+0.101
$[90_3/0_3]_s$	3430	0.588+0.065	0.255+0.028	0.852+0.045

5.2 ANALYSIS OF CUMULATIVE EVENTS VS. STROKE :

Figure 5.12 shows the variation of cumulative events plotted with stroke. The graph shows an increasing trend in all cases with higher event rates in the initial stages upto 40% stroke. The high initial rate of event occurrence is primarily due to yield of material and initial debonding. Such initial high event rate has been reported in [32 - 34].

Among the unidirectional laminates $[0_{12}]$ samples had the maximum number of events and $[90_{12}]$ the minimum. The total events for $[45_{12}]$ sample were between that of $[0_{12}]$ and $[90_{12}]$.

In Crossply laminate $[90_3/0_3]_s$ samples had high initial event rate but progressed at a slow rate after 70% stroke. In case of $[0_3/90_3]_s$ laminate the increasing trend continues upto 100% stroke. This may be due to fibers in 0^oply in $[0_3/90_3]_s$laminate carrying higher load compared to the 0^o ply in $[90_3/0_3]_s$. laminate.

5.3 STATISTICAL CLUSTER PLOT ANALYSIS :

Statistical cluster plots are other methods to represent the data using the statistical results detailed in section 5.1 . Fig. 5.13 shows a typical crossplot between two AE parameters. This plot in the present form does not offer any conclusive information for damage analysis. Hence, plots with respect to the statistical mean and standard deviation of two parameters were generated using the software "CROSSPRO". The selection of the mean and standard deviation as a base for statistical classification is justified as follows.

1. A study of event listing in high fiber volume and epoxy sample was made. It was found that events in the high fiber volume sample had PA > 60 and ED > 100 ,while in the epoxy sample the PA was < 32 and ED < 30.

2. A study of literature [20,35,36] indicated that events with low PA and low ED are due to matrix failure and those due to high ED and high PA are due to fiber failure.

3. For the Kevlar /epoxy laminate tested the events were grouped into classes of $\pm \sigma$ limits. In general all events within $X_{PA} - \sigma_{PA}$ and $X_{ED} - \sigma_{ED}$ were having PA < 32 and ED < 30. Also all events above $X_{PA} + \sigma_{PA}$ and $X_{ED} + \sigma_{ED}$ had PA > 60 and ED > 100. It is to be mentioned that this criterion has been found in all Kevlar samples of volume fraction 55% , crowfeet weave used in this investigation. Hence the selection of ± limits is not a generalized one. The selection of $\pm \sigma$ limits has been previously used in spectral analysis of fiber composite failure mechanism by William and Eagan [37].

With the above base a hypothetical division of the ED vs. PA crossplot region was formulated. With the $\pm\sigma$ limits applied the entire zone was divided into nine blocks. Fig. 5.14 shows the range values for each block. Events falling in each block were represented by special characters. When the crossplot drawn by identifying events falling in each block are interposed with the hypothetical division, it can be seen that maximum number of events (about 60%) occurred between the $\pm\sigma$ limits of the mean. The cluster plot for $[0_{12}]$, $[45_{12}]$, and $[90_{12}]$ samples with the block representation showing the percentage of events in each block is shown in Fig.5.15 to 5.17. While the damage characteristic of the events in block 1 representing matrix failure and block 9 representing fiber failure are known, the damage mechanism represented by the other blocks were not specific .

Table 5.18 gives the details of the mean, standard deviation and percentage of events in each block (with respect to Fig.5.13) for unidirectional laminates, high fiber volume laminate epoxy specimens and crossply laminates. It can be seen that the percentage of events due to pure fiber or matrix failure is less.

In the case of fiber rich samples one observation was made during the experiment. The sample exhibited delamination of plies. The cause for delamination can be explained as follows. In the high fiber volume sample , the proportion of epoxy is only 10 to 15% by volume . A crack propagating through a ply in the laminate may get arrested as the crack tip reaches the fiber in adjacent ply. Due to the arrest the events occurring will have a low Peak amplitude . The event duration will be greater because the high shear stress in the matrix adjacent to the crack tip may

cause the crack to branch off and start running at the interface parallel to the plane of the plies. The events corresponding to

TABLE 5.18

Sample configuration.	Total no. of events.	Mean FA	Mean ED	Standard deviation FA	Standard deviation ED	Event percentage in blocks 1	2	3	4	5	6	7	8	9
$[0_{12}]$	2860	46	70	13	45	9.75	3.2	-	6.32	62.4	3.8	-	3.6	10.8
$[90_{12}]$	1416	45	67	13	47	8.2	4.9	-	5.4	65.1	3.5	-	2.4	9.8
$[45_{12}]$	2243	42	64	09	39	6.7	2.6	-	6.0	68.5	3.6	-	3.2	9.0
High fiber volume	900	55	60	06	45	11.4	0.45	-	24.7	25.4	11.5	-	0.6	25.0
Epoxy	45	35	44	04	11	89	0.6	-	1.1	3.2	3.0	-	1.0	3.0
$[0_3/90_3]_s$	4270	50	66	15	44	10.2	3.9	-	4.4	63.8	5.0	-	1.3	11.1
$[90_3/0_3]_s$	3431	47	68	12	40	7.4	3.2	-	3.5	69.5	3.6	-	2.5	9.9

this mechanism in high fiber volume sample is 24.7% (Block 4) while in the composite samples it is 6.3 , 5.4 and 6.0 percent for $[0_{12}]$, $[90_{12}]$ and $[45_{12}]$ laminates respectively.

Fig.5.19 and 5.20 show the statistical cluster plot for the crossply laminates $[0_3/90_3]_s$ and $[90_3/0_3]_s$. In comparison with other unidirectional laminates, there does not exist any distinguisable dominance of events in any block. The center block which represent interface failure is predominant as in unidirectional laminate.

The percentage of events in each block of $[90_3/0_3]_s$ laminate is well comparable to the percentage of events in the same block of $[90_{12}]$ laminate. Similar is the case where $[0_3/90_3]_s$ laminate follow with $[0_{12}]$ laminate. It can thus be inferred that the

failure mechanism in crossply laminate follow to a certain extent the unidirectional laminate

While a study of such clustering gives an idea of some important damage mechanism , another good indicator would be the histogram type of displays

5.5 HISTOGRAM OF PEAK AMPLITUDE AND EVENT DURATION :

Histogram displays indicate the variation in number of events at different stroke levels This gives pertinent information on the rate at which events occur in different ranges. Fig. 5 21 to Fig 5.26 show the histogram plots from 10% to 100% stroke level for unidirectional laminates. From the plots it can be observed that :

1. Upto 20% stroke most events are in the low value ranges. Small number of events in the high value range occur in $[0_{12}]$ laminates indicating fiber failure at initial loading due to stress concentration at the notch tip.

2. The number of events are greater in the middle range of ED and PA signifying the predominance of interface failure mode.

3 The plots tend to follow a pattern from 0 to 100% stroke level. Two visible peaks can be observed in both ED and PA plots signifying two distinct microfracture processes.

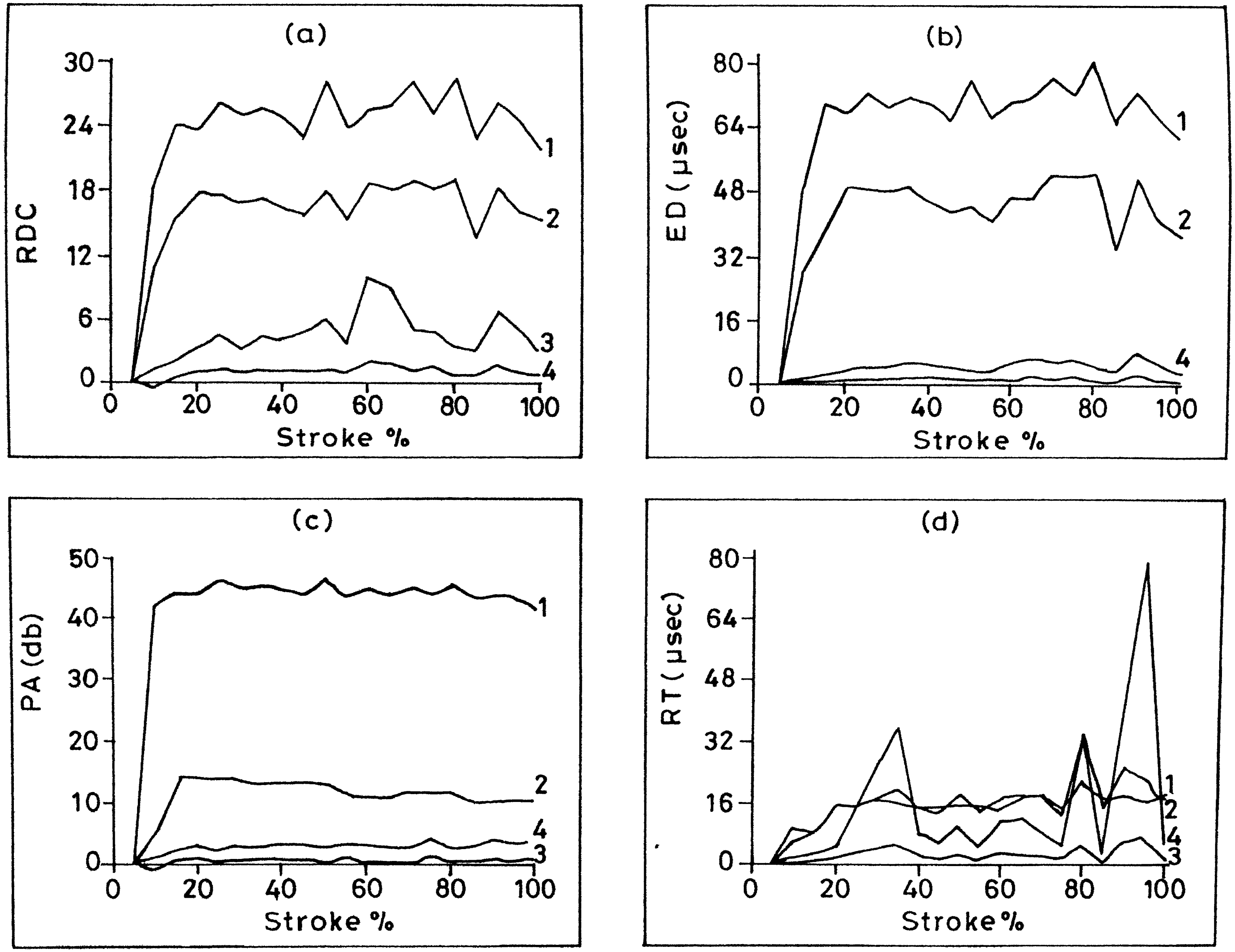
4. The PA and ED histograms indicate the normal distribution pattern with a heavier right tail. This is supported by the positive value of skewness in all cases from statistical data.

Fig.5.27 - 5.30 shows the PA and ED histograms for crossply laminates. Event generation in $[0_3/90_3]_s$ laminate at the two extreme ends is higher compared to $[90_3/0_3]_s$ laminate

indicating dominance of matrix failure and fiber failure

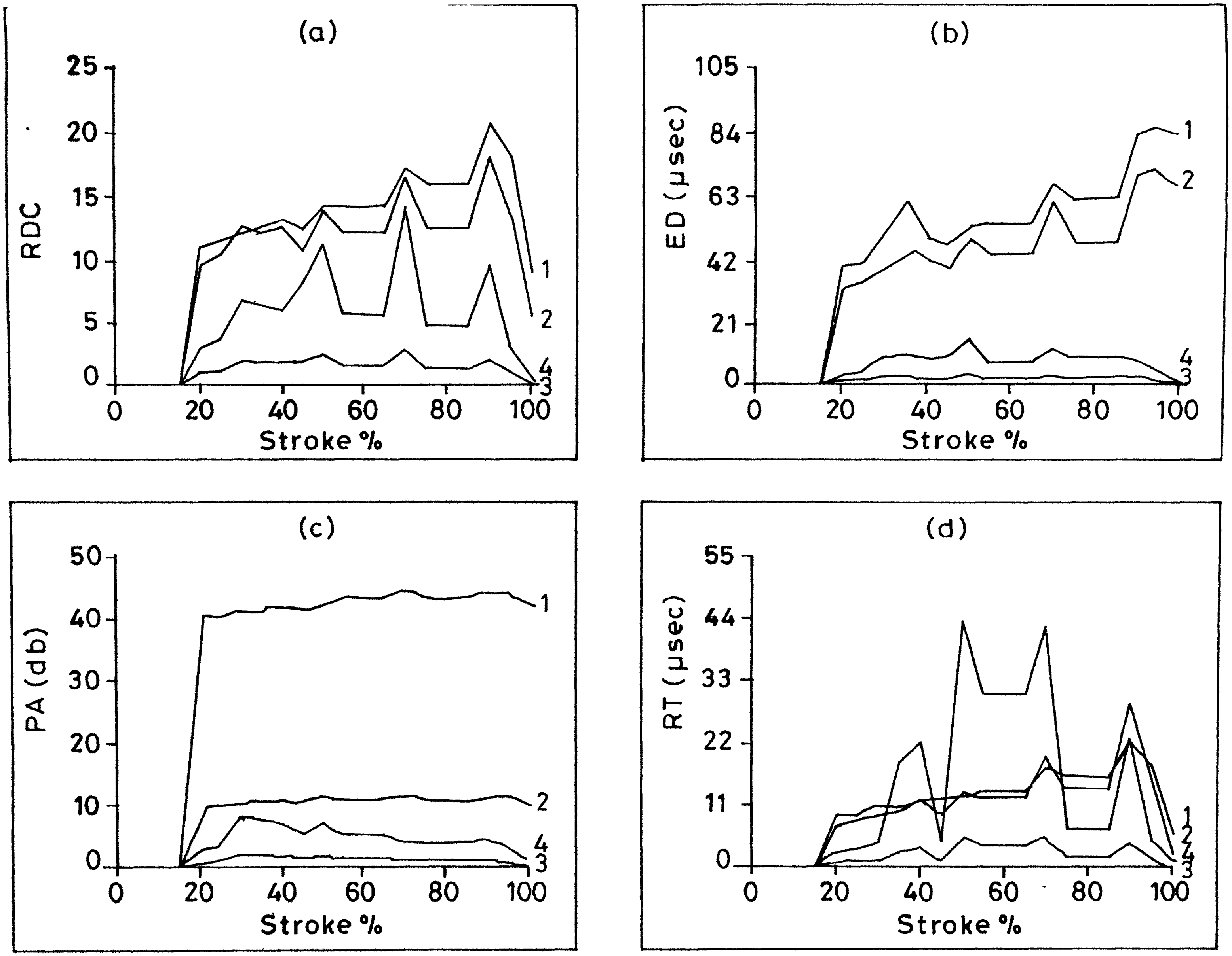
Two distinct peaks can be seen in the event distribution vs. ED histograms (Fig. 5 29, 5 30) in crossply laminates than in unidirectional laminates. As these peaks are at low amplitude and middle amplitude range they can be associated with matrix cracking and distinct interface failure.

The statistical analysis, crossplots and histogram displays have helped to formulate an approach to study the different damage mechanisms. Though all damage mechanisms could not be identified in the present investigation , the approach leads a way for further detailed analysis.



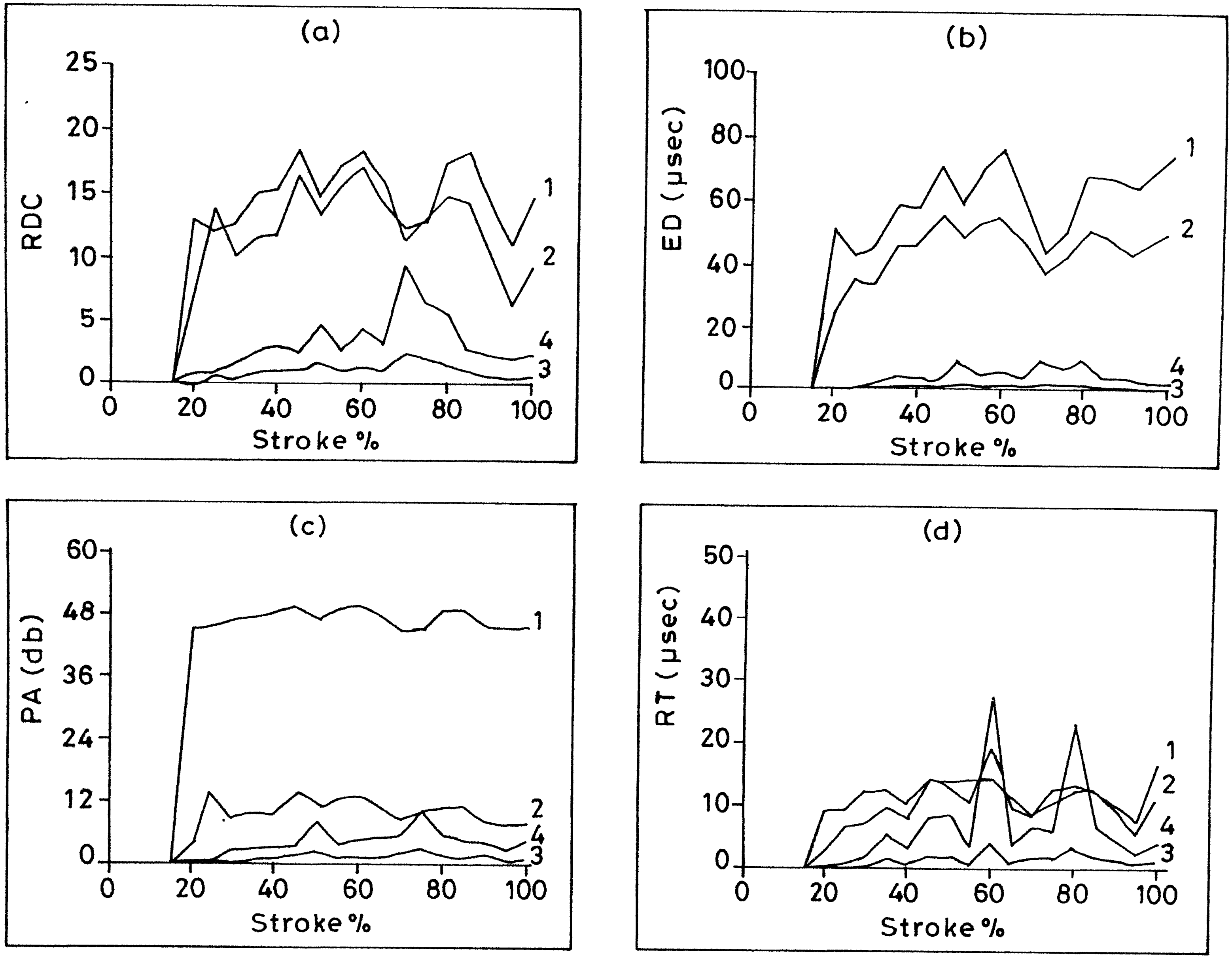
Index: 1- Mean; 2-Standard deviation; 3- Skewness; 4-Kurtosis

Fig. 5.1 Range plots for $[0_{12}]$ laminate



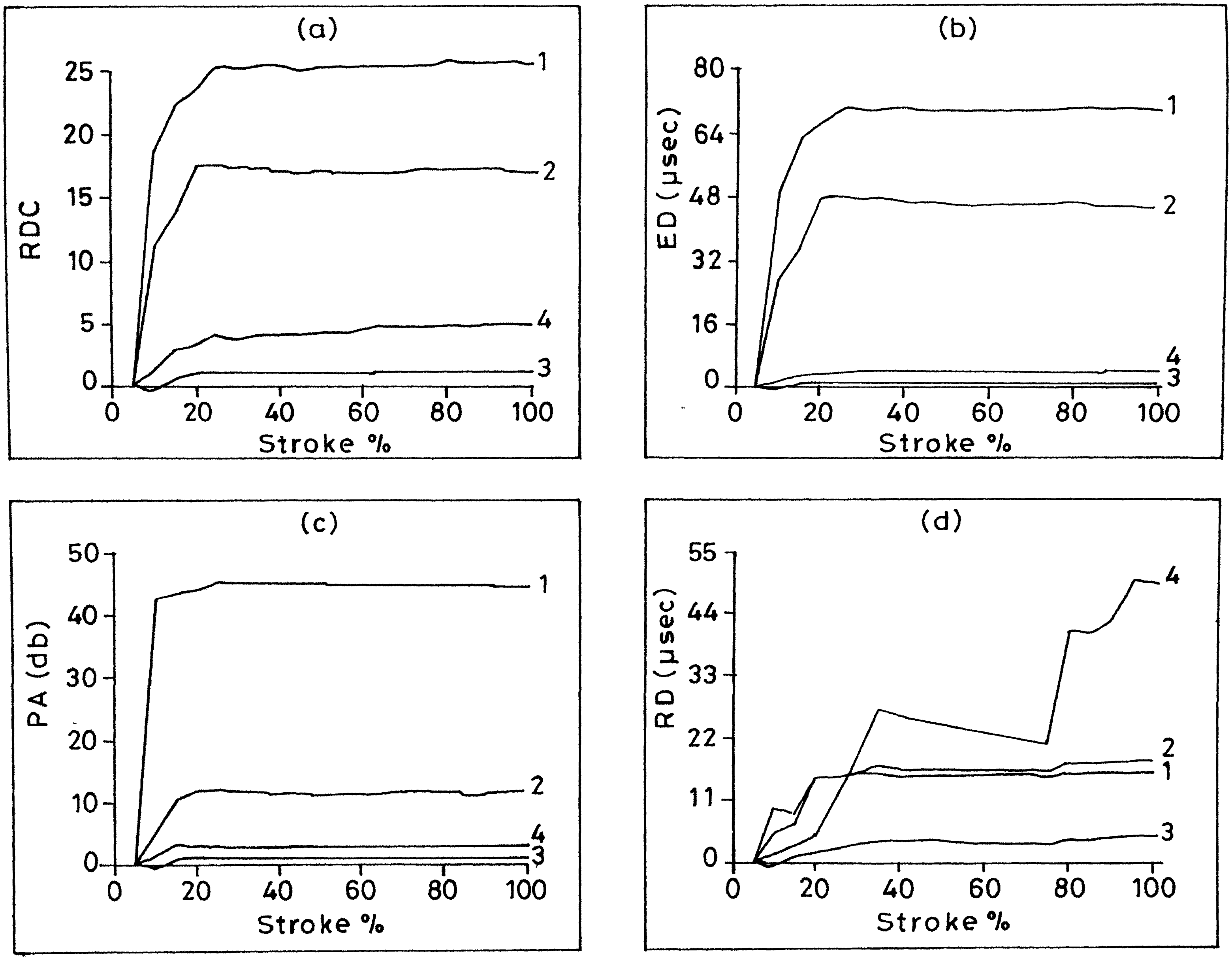
Index : 1 - Mean ; 2 - Standard deviation ; 3 - Skewness ; 4 - Kurtosis

Fig. 5.2 Range plots for [45_{12}] laminate.



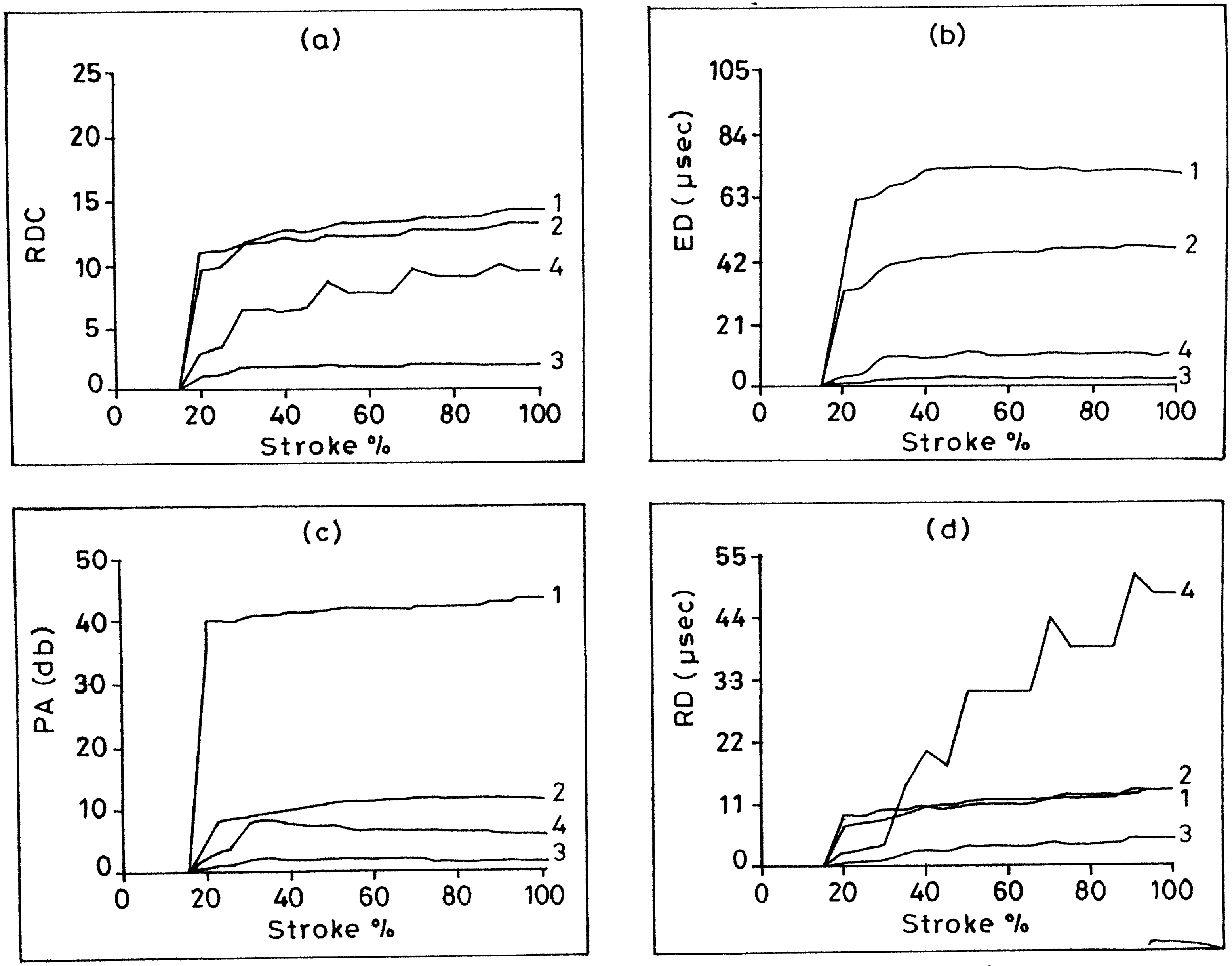
Index: 1-Mean; 2-Standard deviation; 3-Skewness; 4-Kurtosis.

Fig. 5.3 Range plots for $[90_{12}]$ laminate.



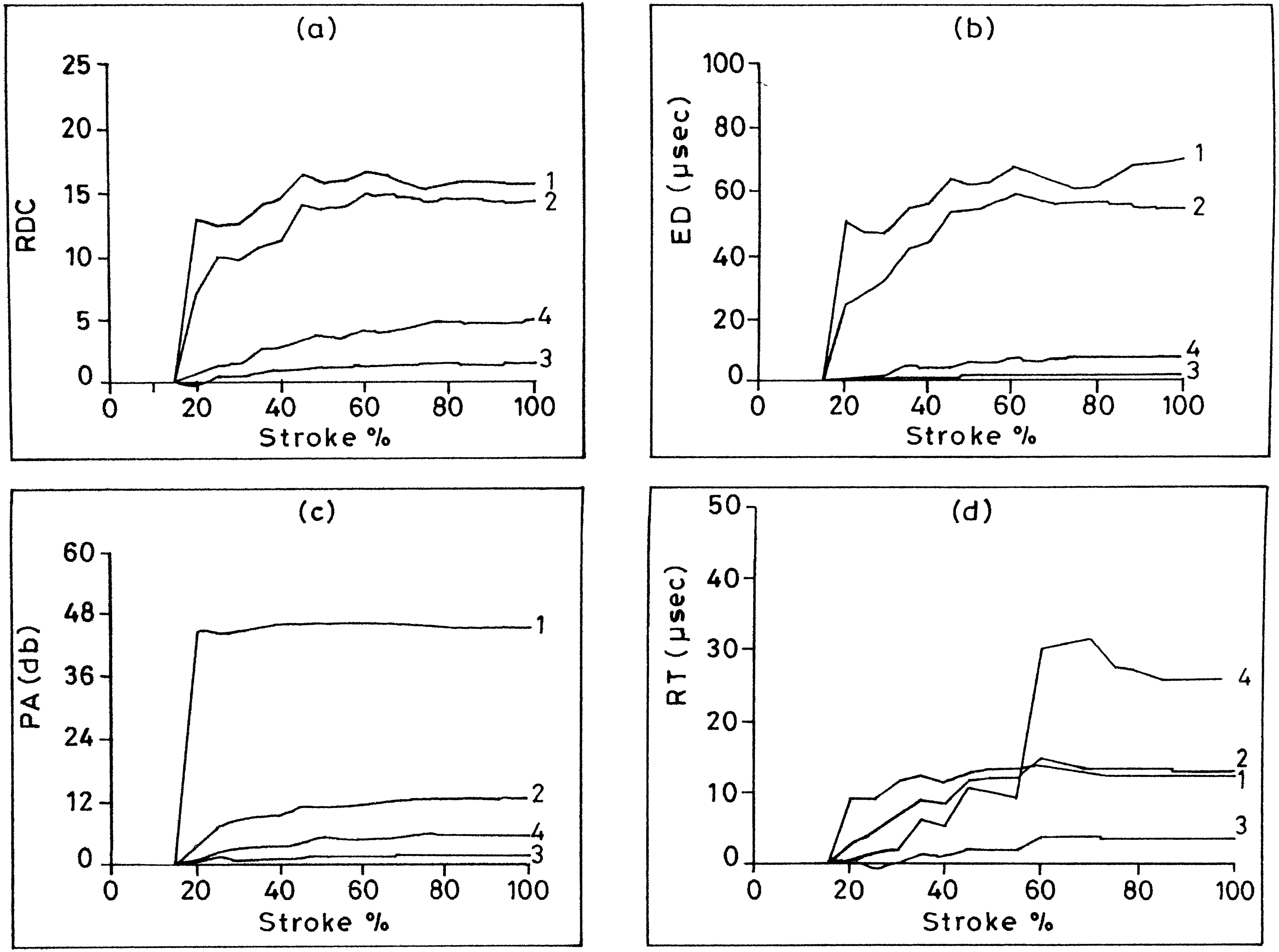
Index : 1-Mean ; 2-Standard deviation ; 3-Skewness ; 4-Kurtosis

Fig. 5.4 Cummulative plots for [0_{12}] laminate.



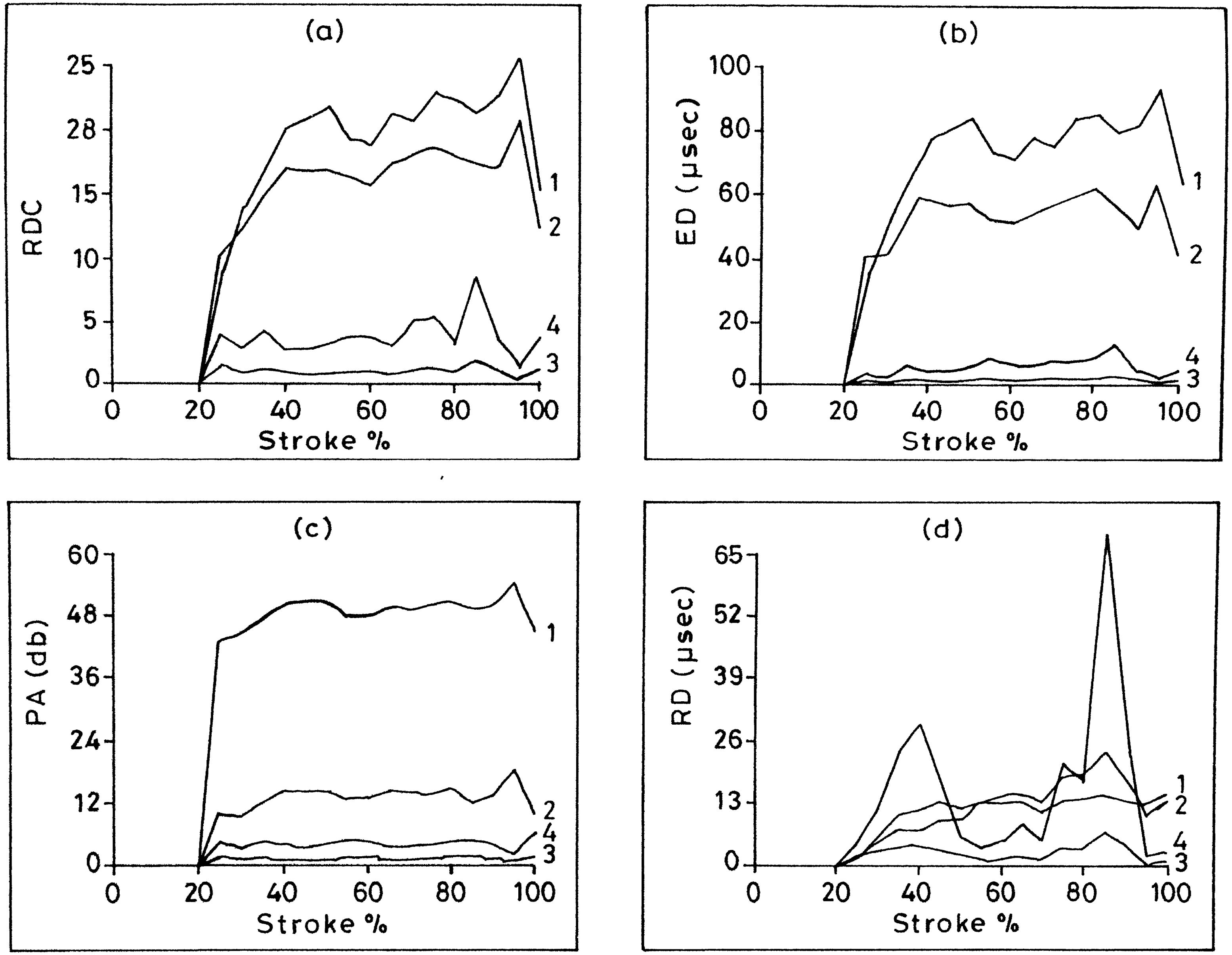
Index : 1- Mean ; 2-Standard deviation ; 3-Skewness ; 4-Kurtosis

Fig. 5.5 Cummulative plots for [45_{12}] laminate.



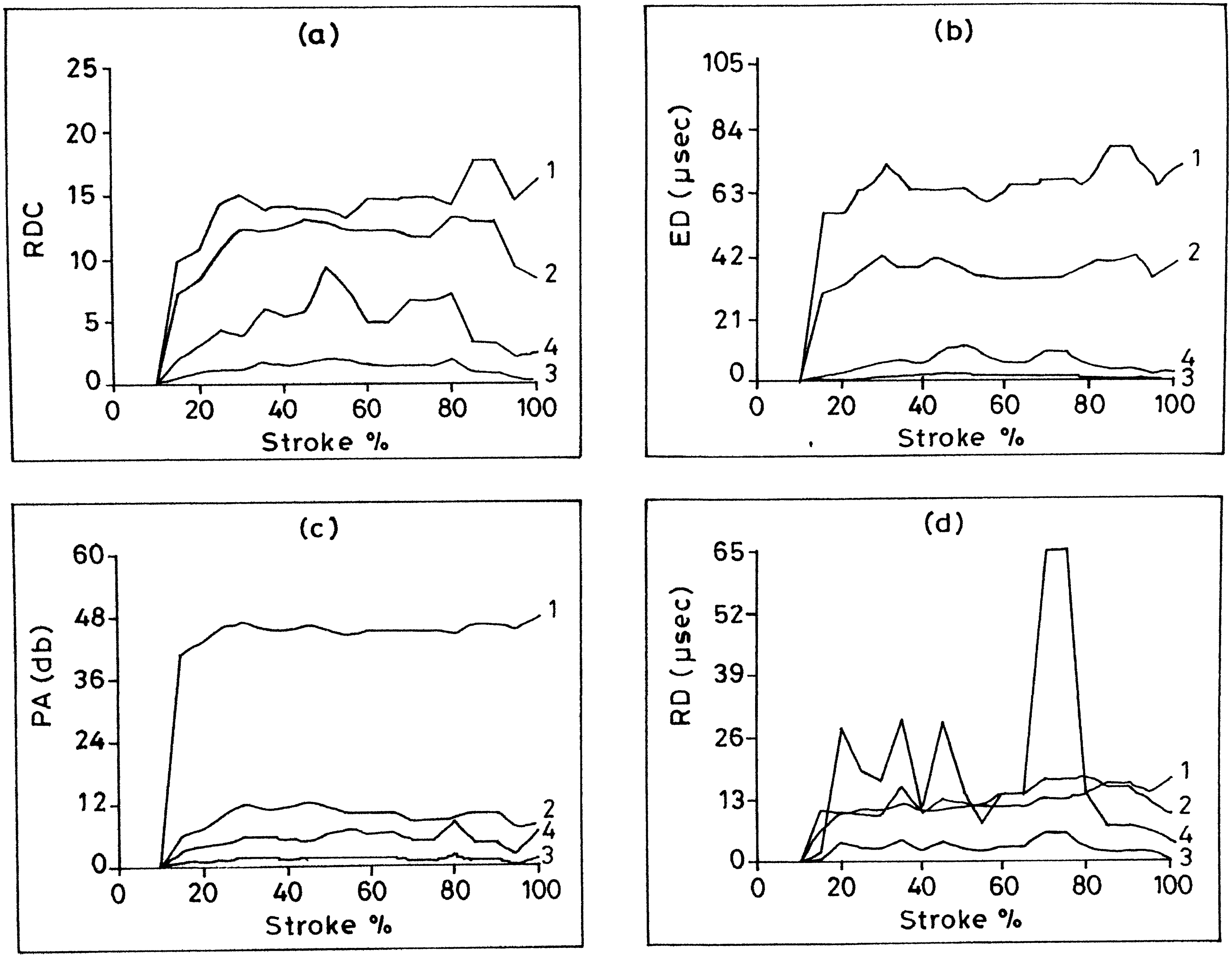
Index: 1- Mean; 2- Standard deviation; 3- Skewness; 4- Kurtosis.

Fig. 5.6 Cummulative plots for $[90_{12}]$ laminate.



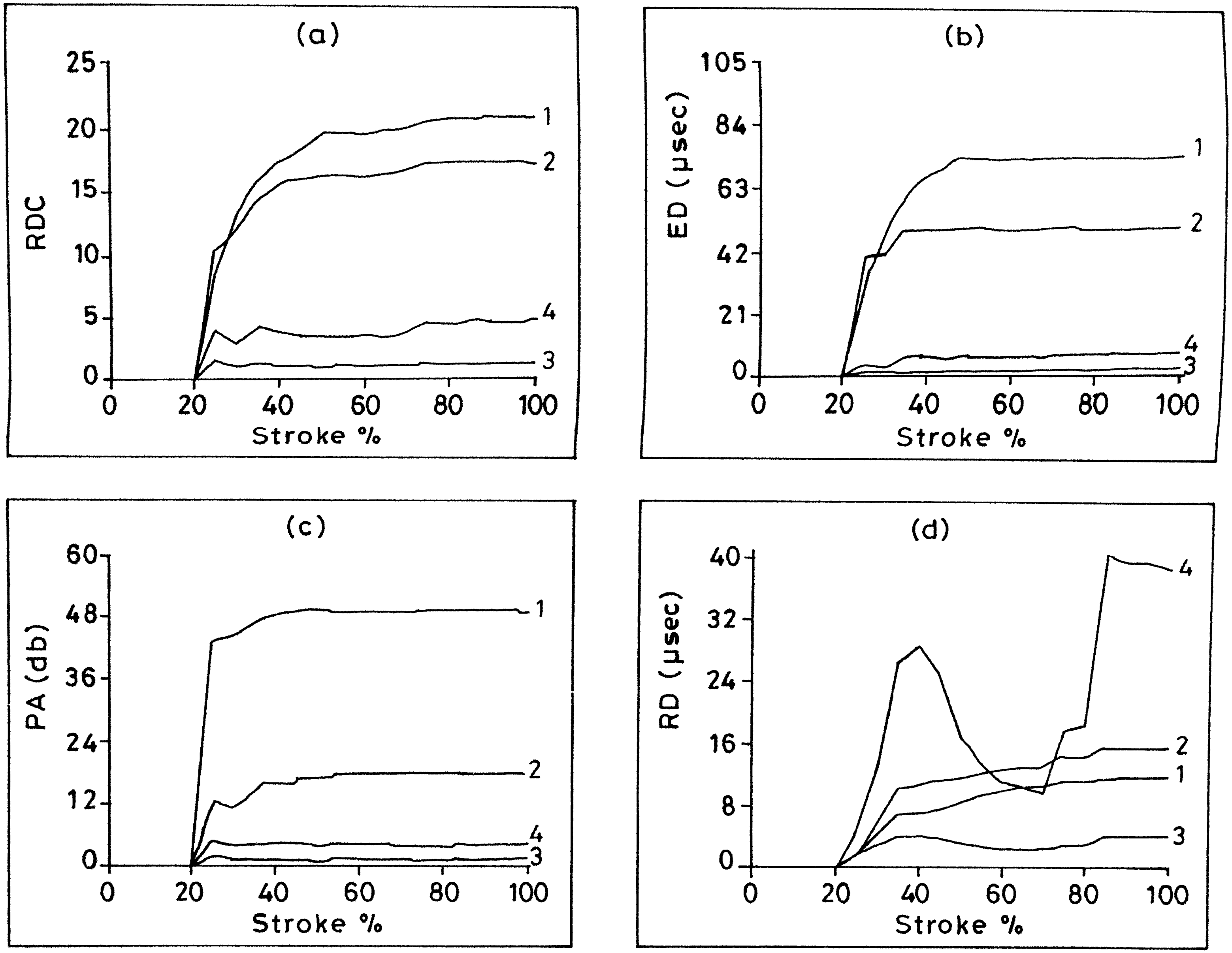
Index : 1 - Mean ; 2 - Standard deviation ; 3 - Skewness ; 4 - Kurtosis

Fig. 5.7 Range plots for $[0_3/90_3]_s$ laminate.



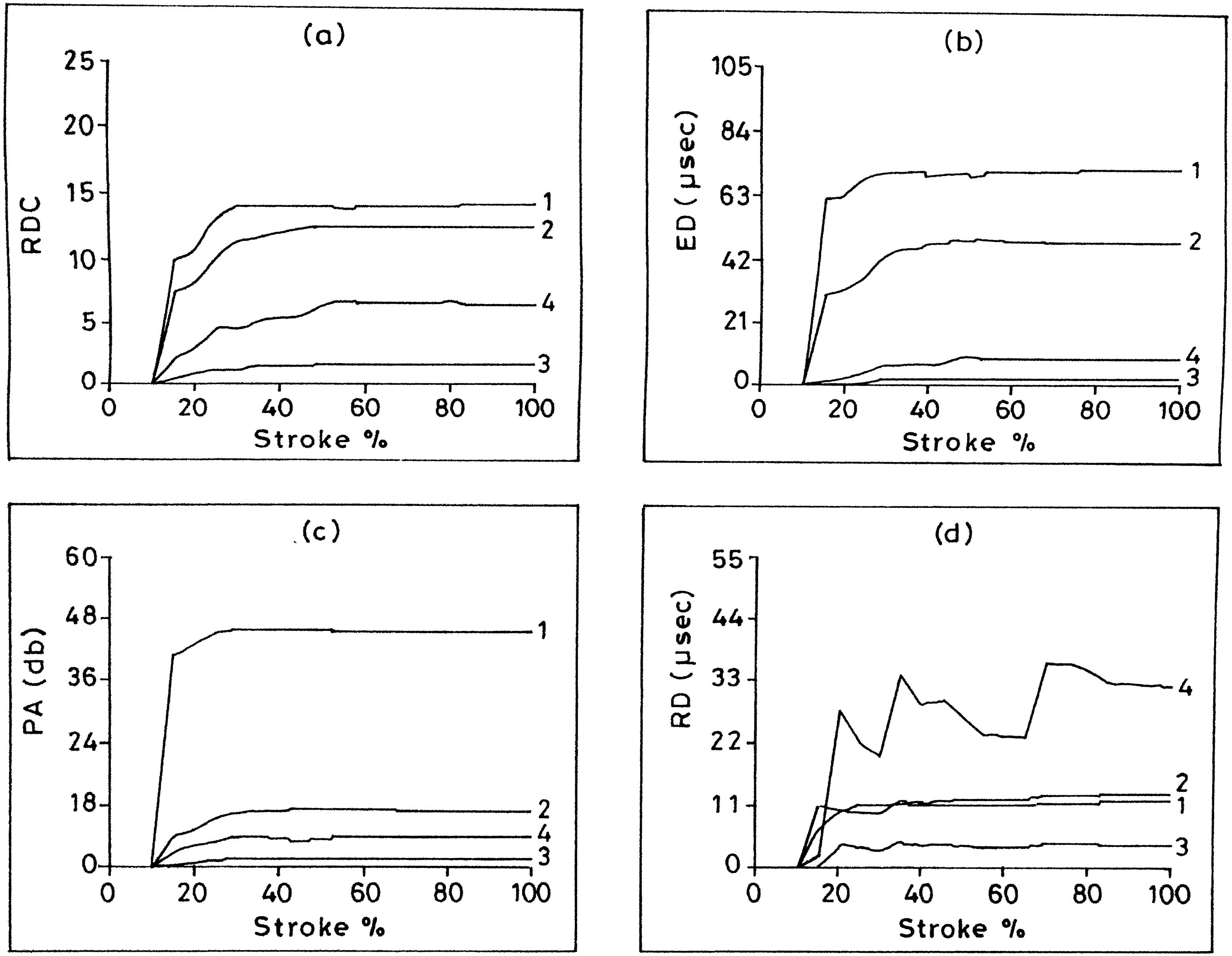
Index: 1-Mean; 2-Standard deviation; 3-Skewness; 4-Kurtosis

Fig. 5.8 Range plots for $[90_3/0_3]$ laminate



Index: 1-Mean ; 2-Standard deviation ; 3-Skewness ; 4-Kurtosis

Fig. 5.9 Cummulative plots for $[0_3/90_3]_s$ laminate.



Index: 1-Mean; 2-Standard deviation; 3-Skewness; 4-Kurtosis

Fig. 5.10 Cummulative plots for $[90_3/0_3]$ laminate.

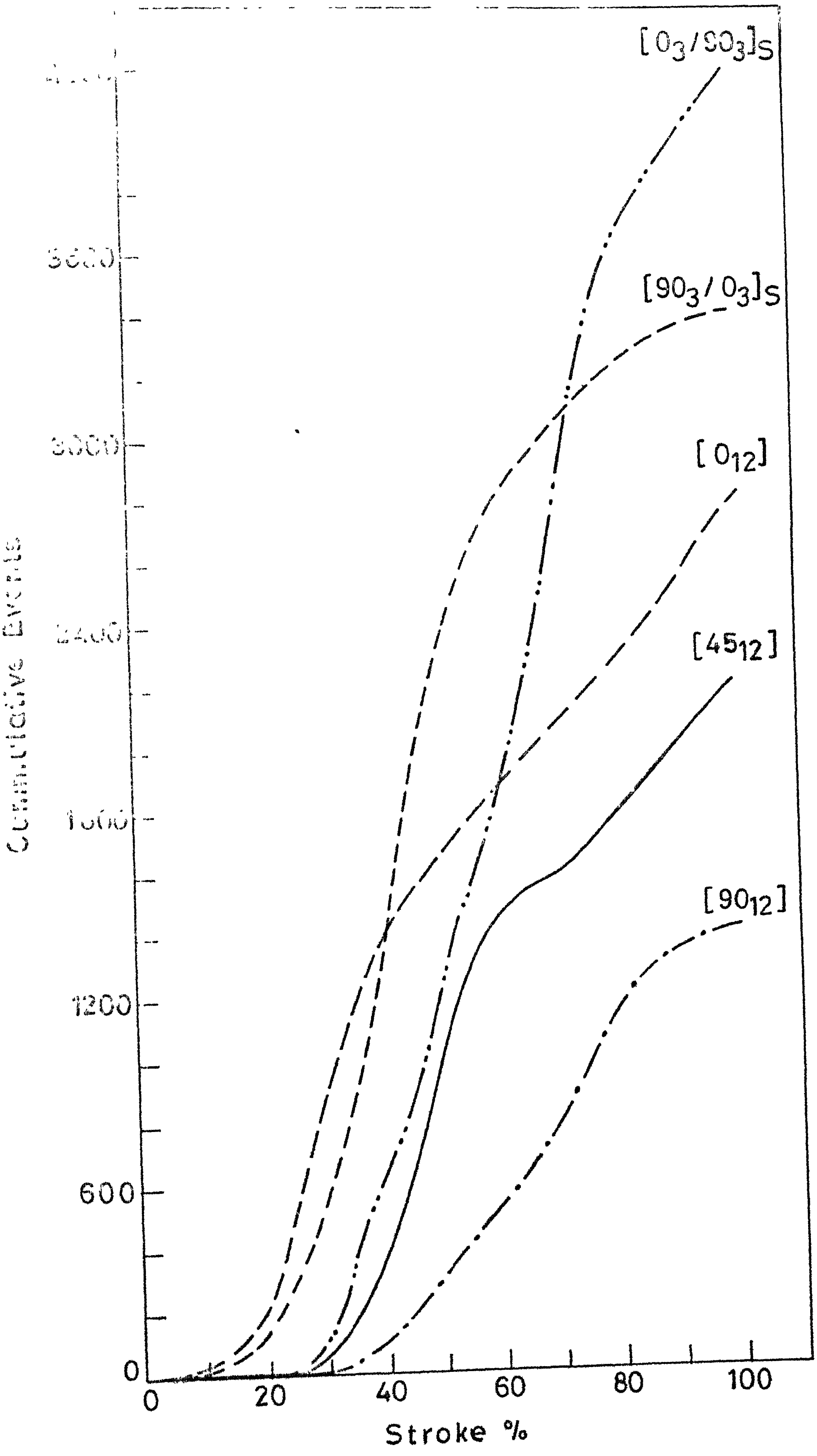


Fig. 5.12 Graph of cummulative events vs. stroke.

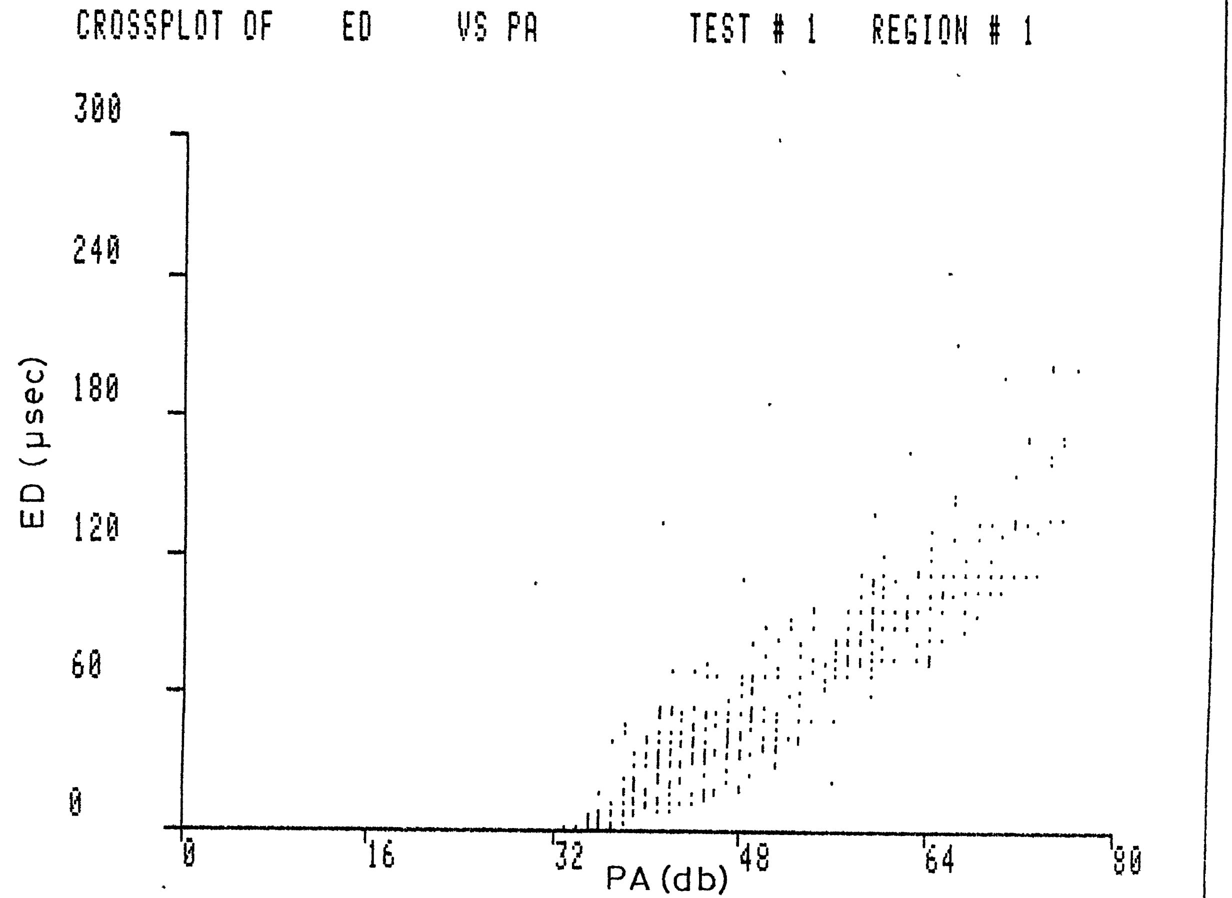


Fig. 5.13 A typical crossplot.

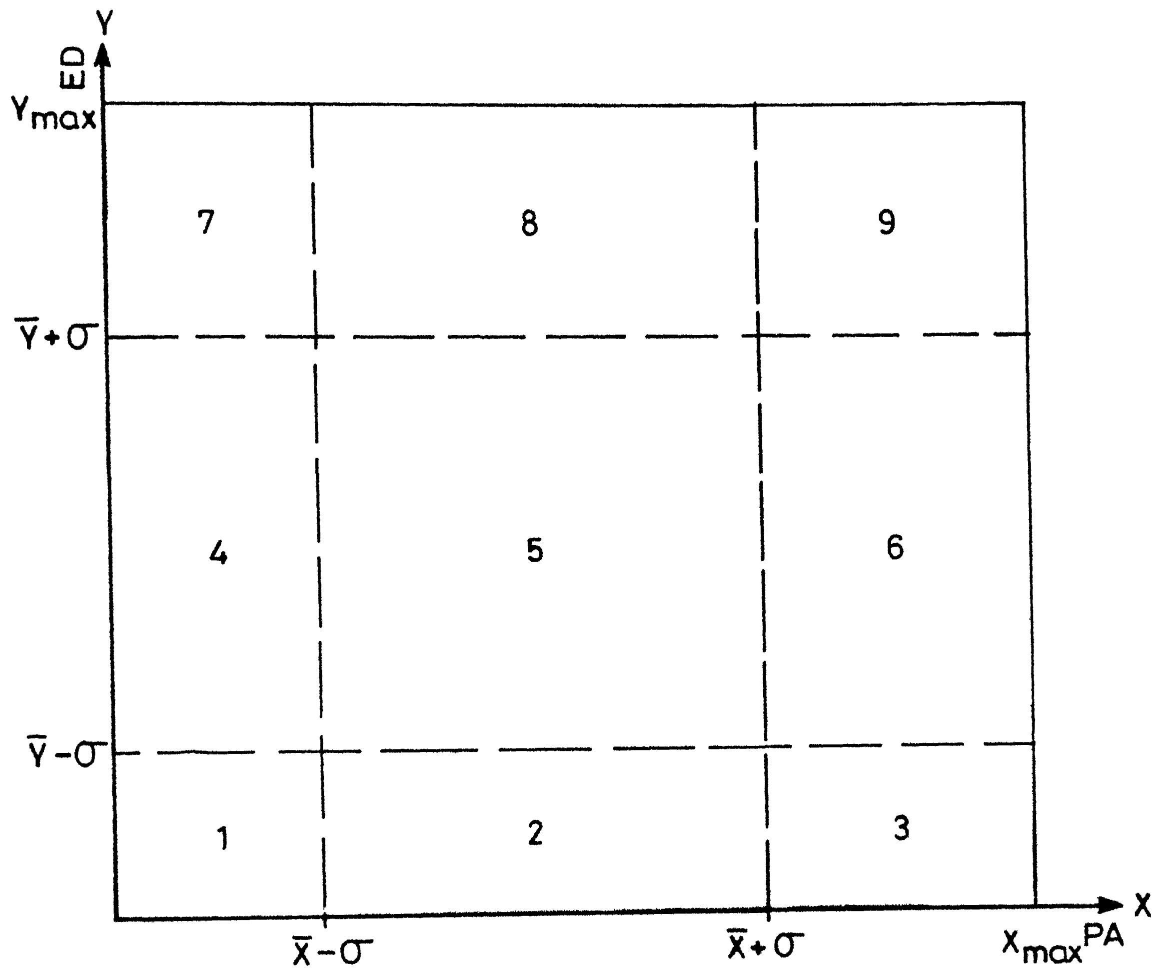


Fig. 5.14 Graph showing block location and range values.

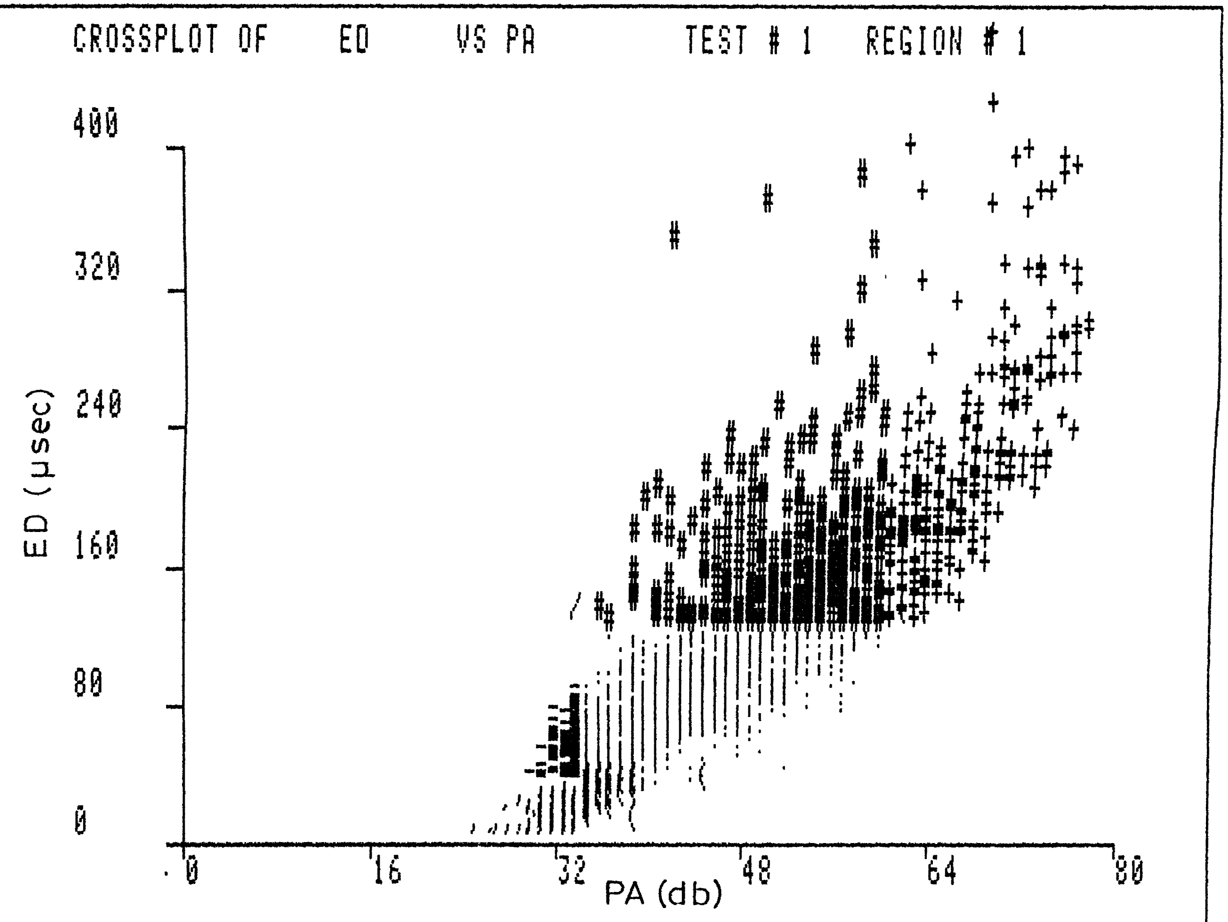


Fig. 5.15 Statistical cluster plot of $[0_{12}]$ laminate.

$\overline{X}_{PA} = 46$, $\overline{X}_{ED} = 70$, $\sigma_{PA} = 13$, $\sigma_{ED} = 45$

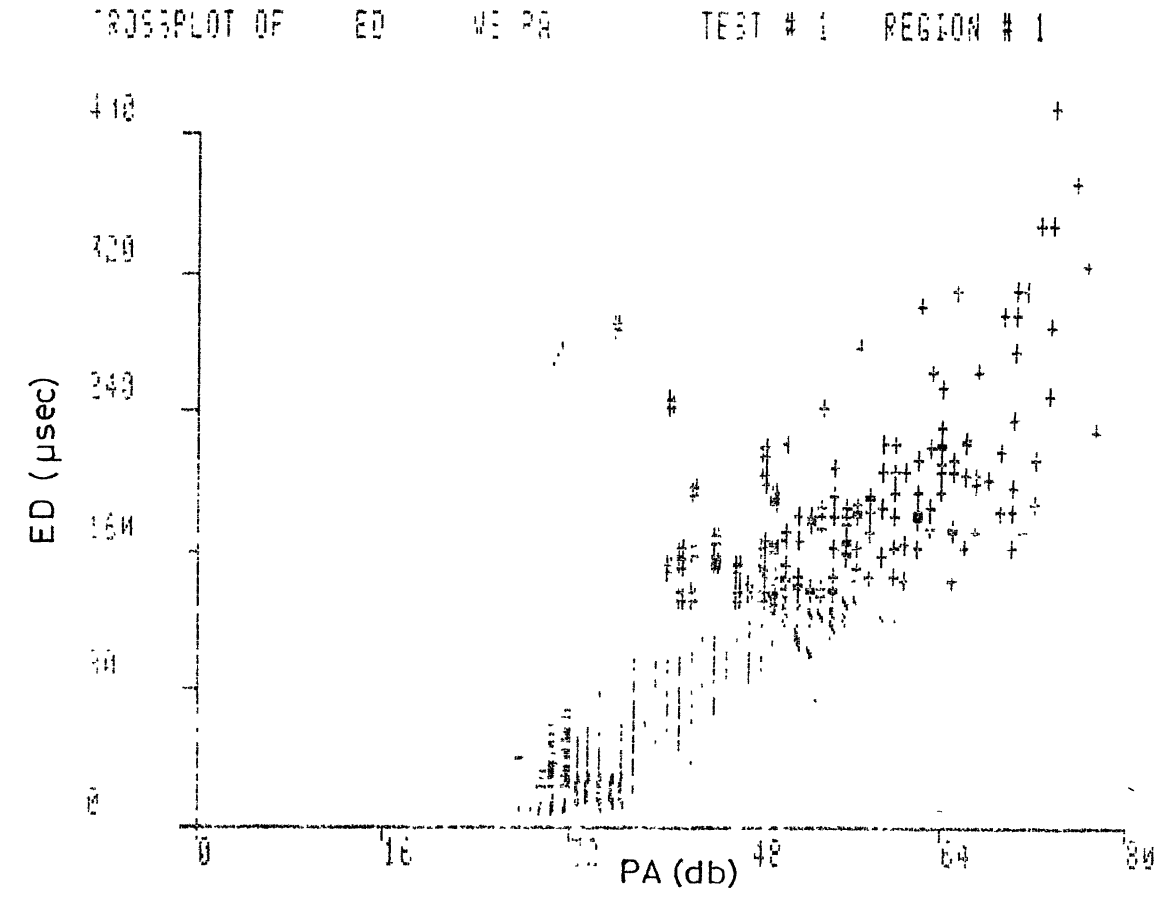


Fig. 5.16 Statistical cluster plot of $[90_{12}]$ laminate..

$\overline{X}_{PA} = 45$, $\overline{X}_{ED} = 67$, $\sigma_{PA} = 13$, $\sigma_{ED} = 47$

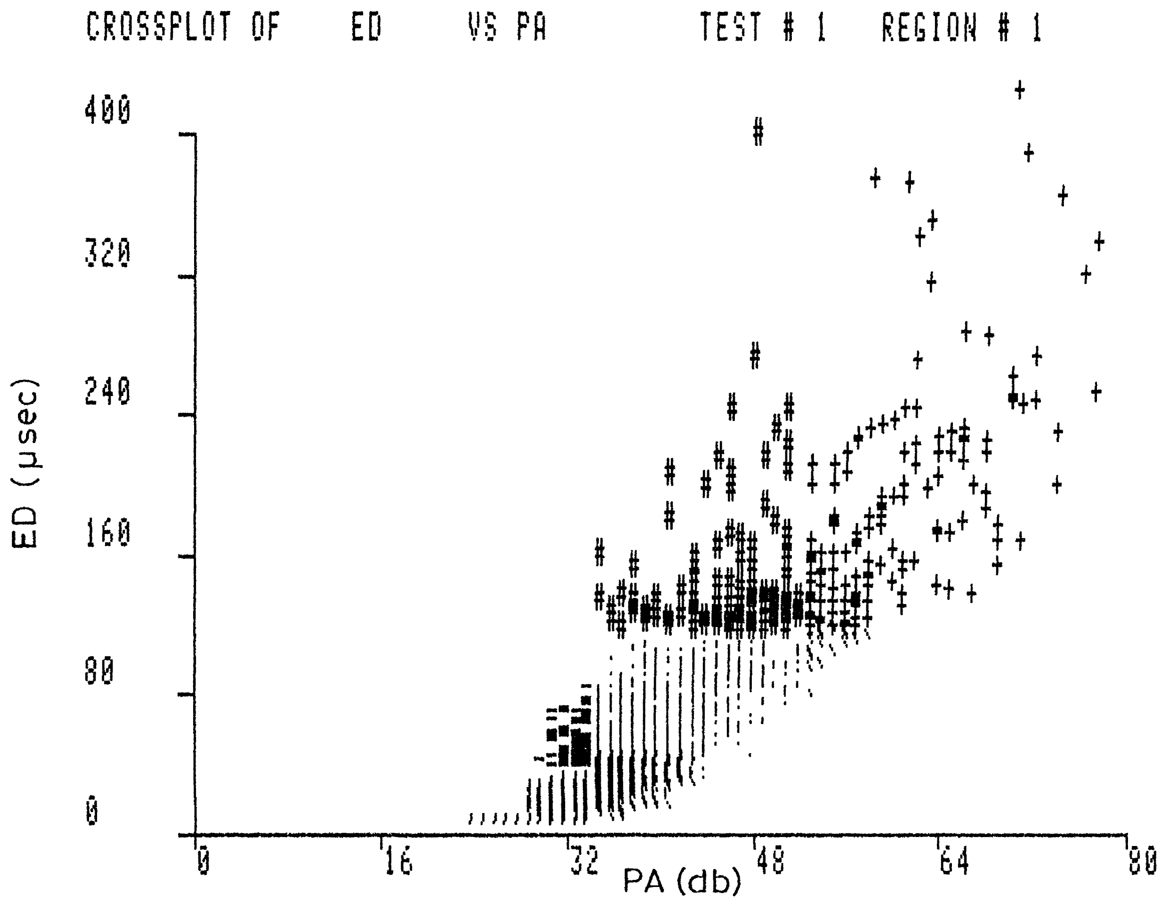


Fig. 5.17 Statistical cluster plot of [45_{12}] laminate.

$\overline{X}_{PA} = 42$, $\overline{X}_{ED} = 64$, $\sigma_{PA} = 9$, $\sigma_{ED} = 39$

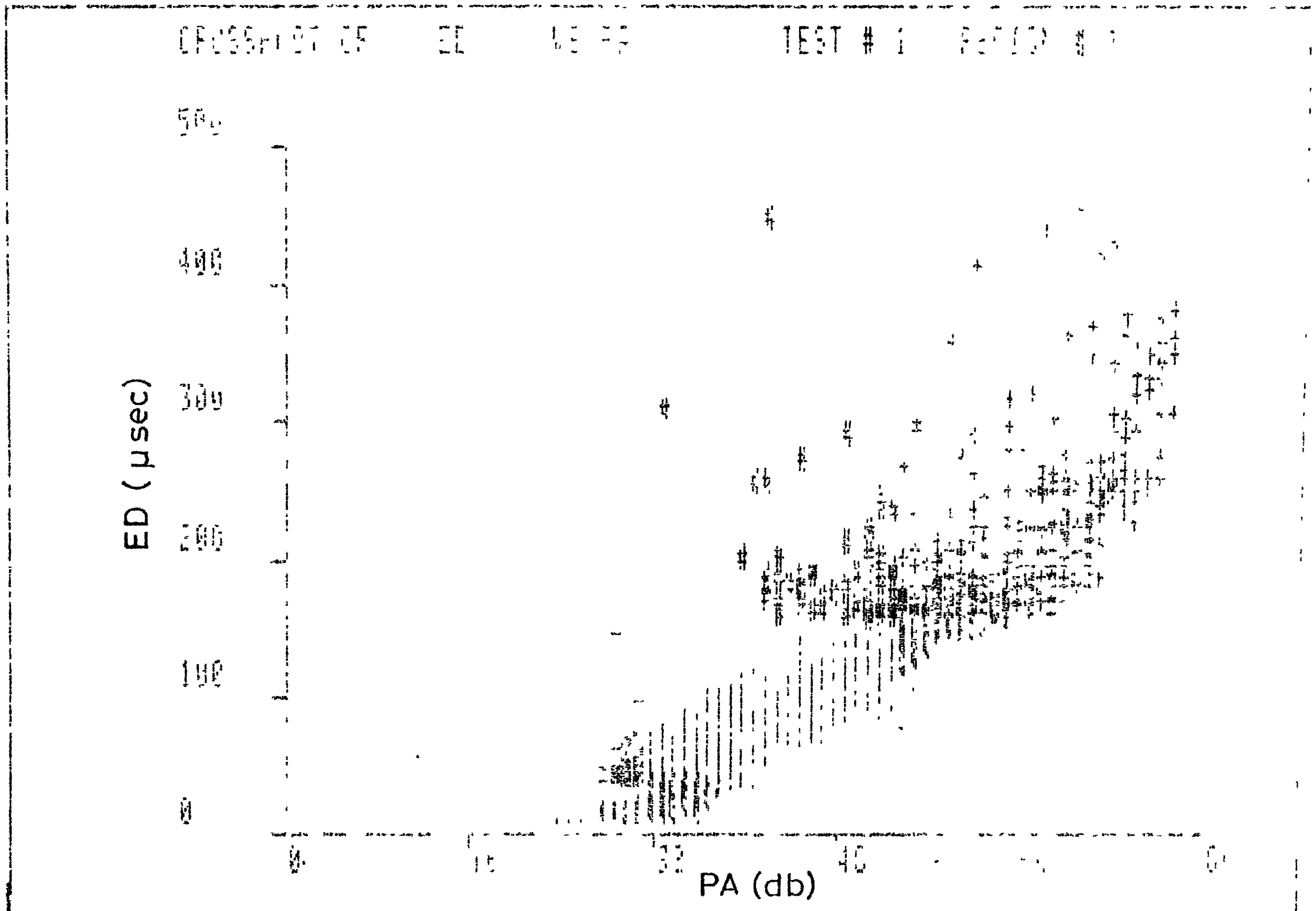


Fig. 5.19 Statistical cluster plot of $[0_3/90_3]_S$ laminate.

$\overline{X}_{PA} = 50$, $\overline{X}_{ED} = 66$, $\sigma_{PA} = 15$, $\sigma_{ED} = 44$

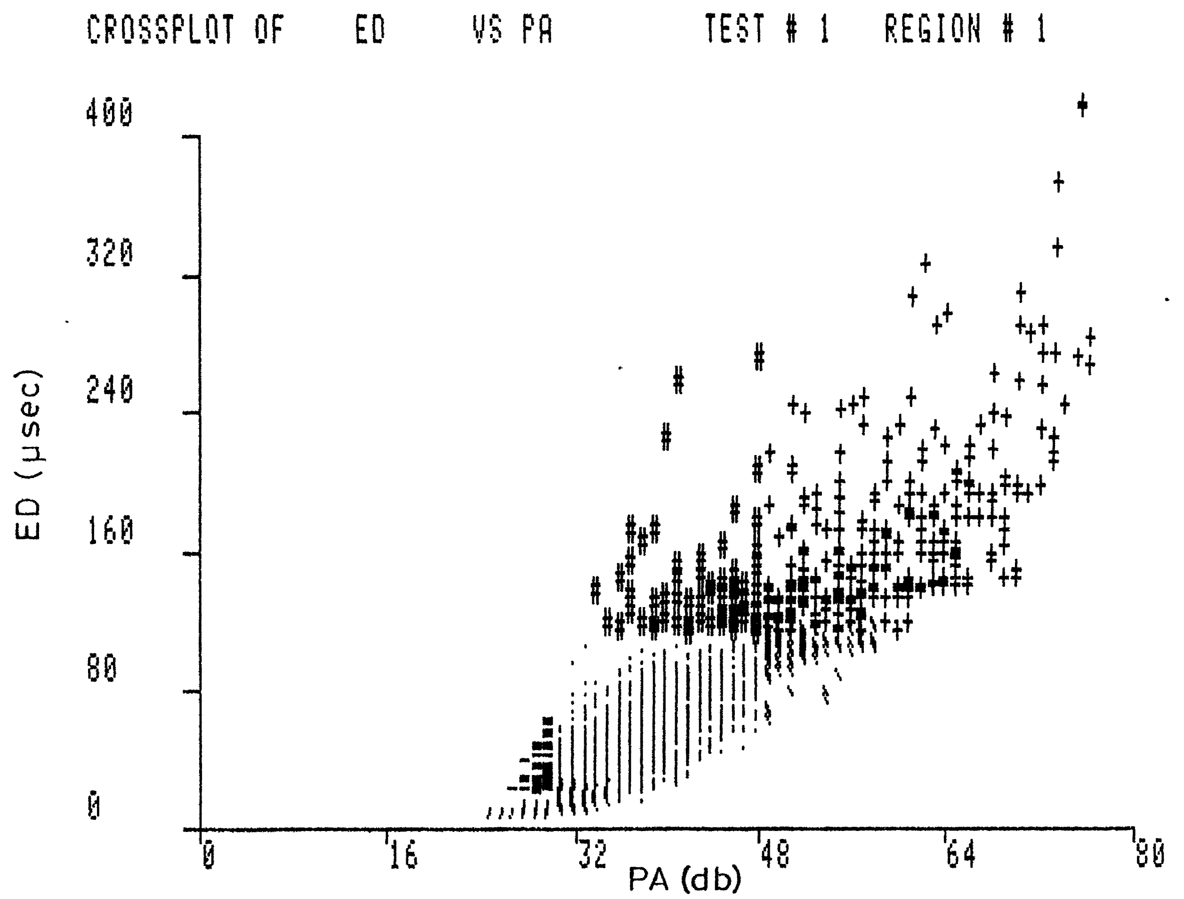


Fig. 5.20 Statistical cluster plot of $[90_3/0_3]_S$ laminate.

$\overline{X}_{PA} = 47$, $\overline{X}_{ED} = 68$, $\sigma_{PA} = 12$, $\sigma_{ED} = 40$

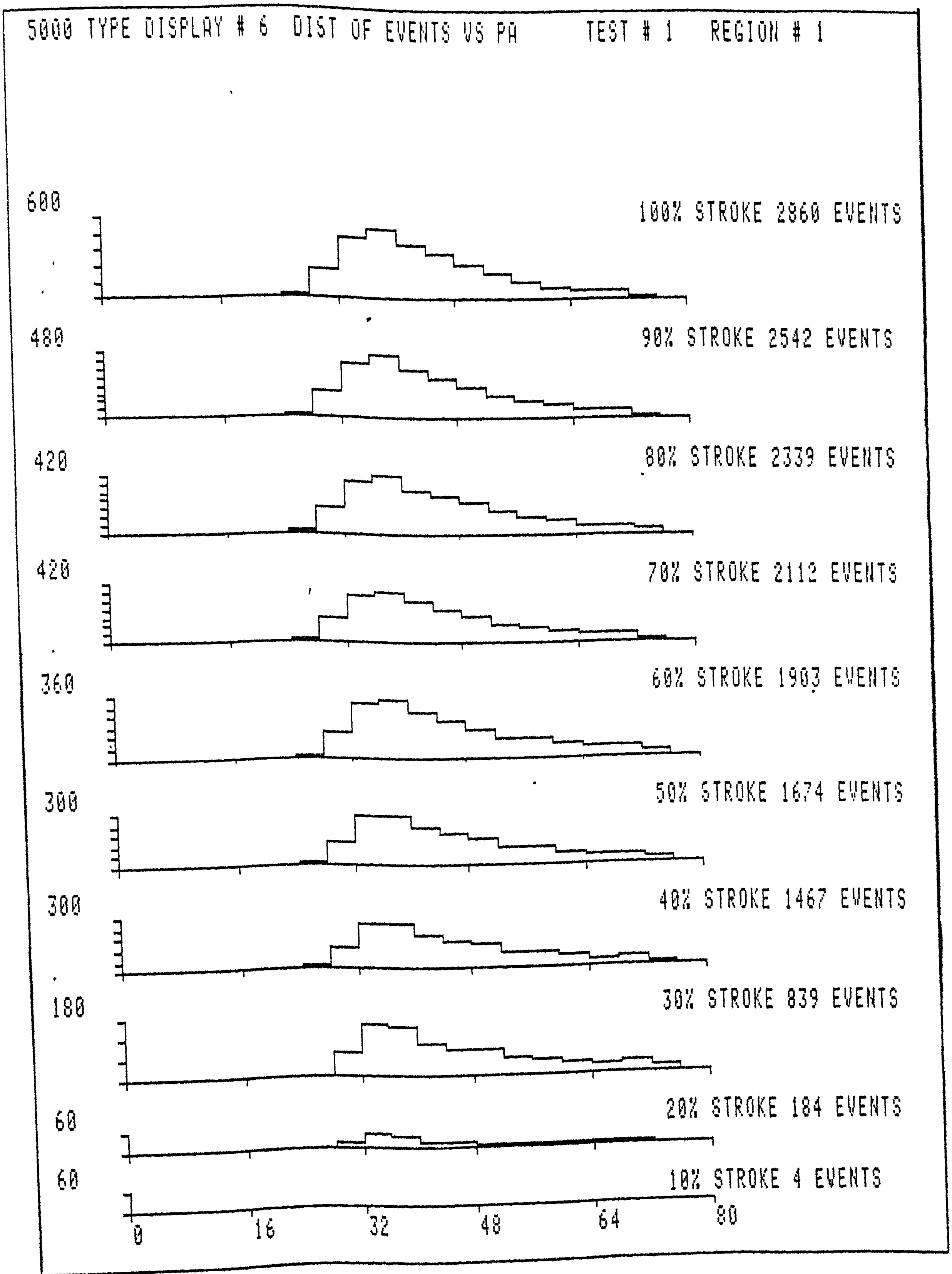


Fig. 5.21 Distribution of events vs peak amplitude of $[0_{12}]$ laminate.

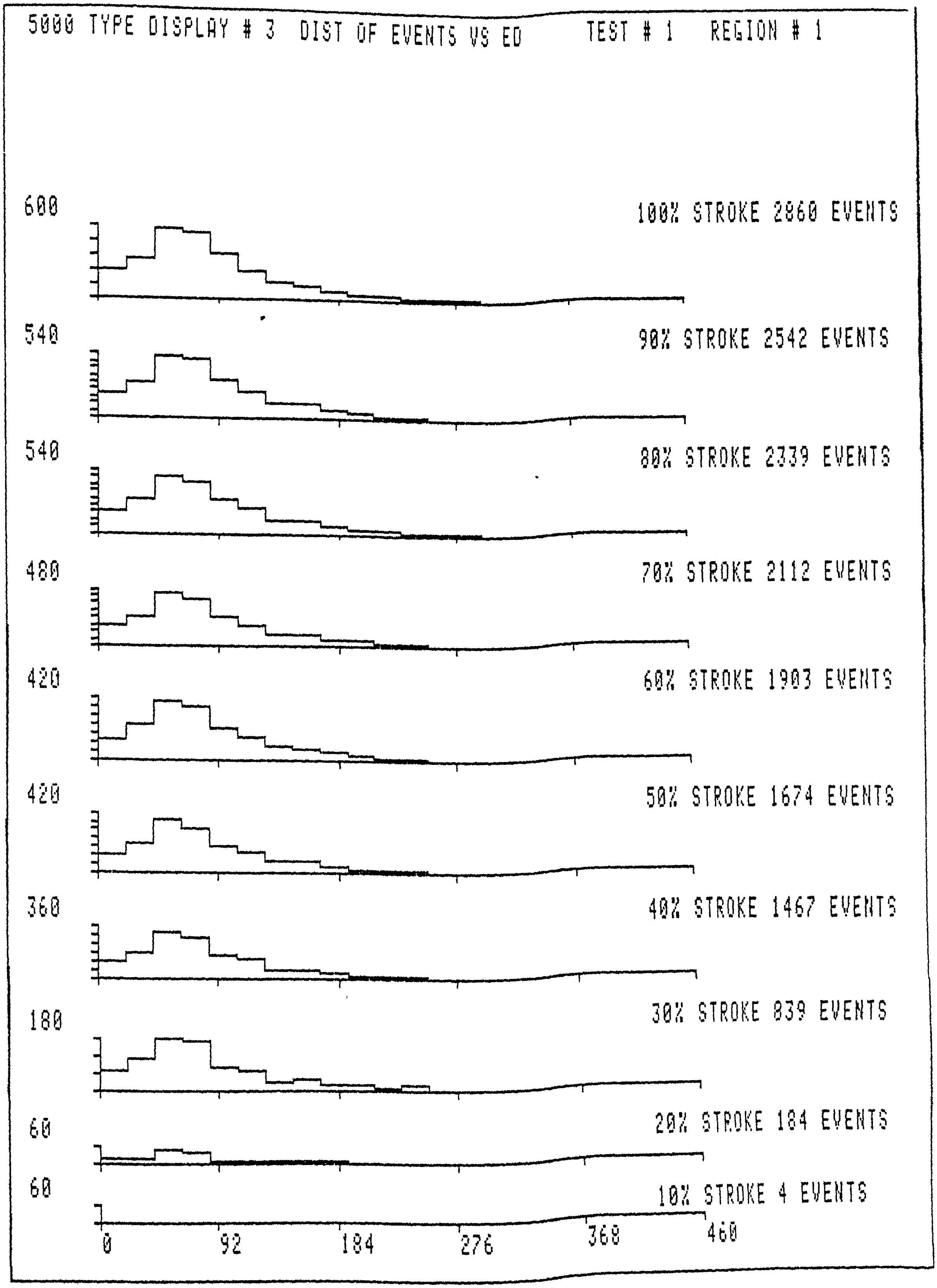


Fig. 5.22 Distribution of events vs event duration of $[0_{12}]$ laminate.

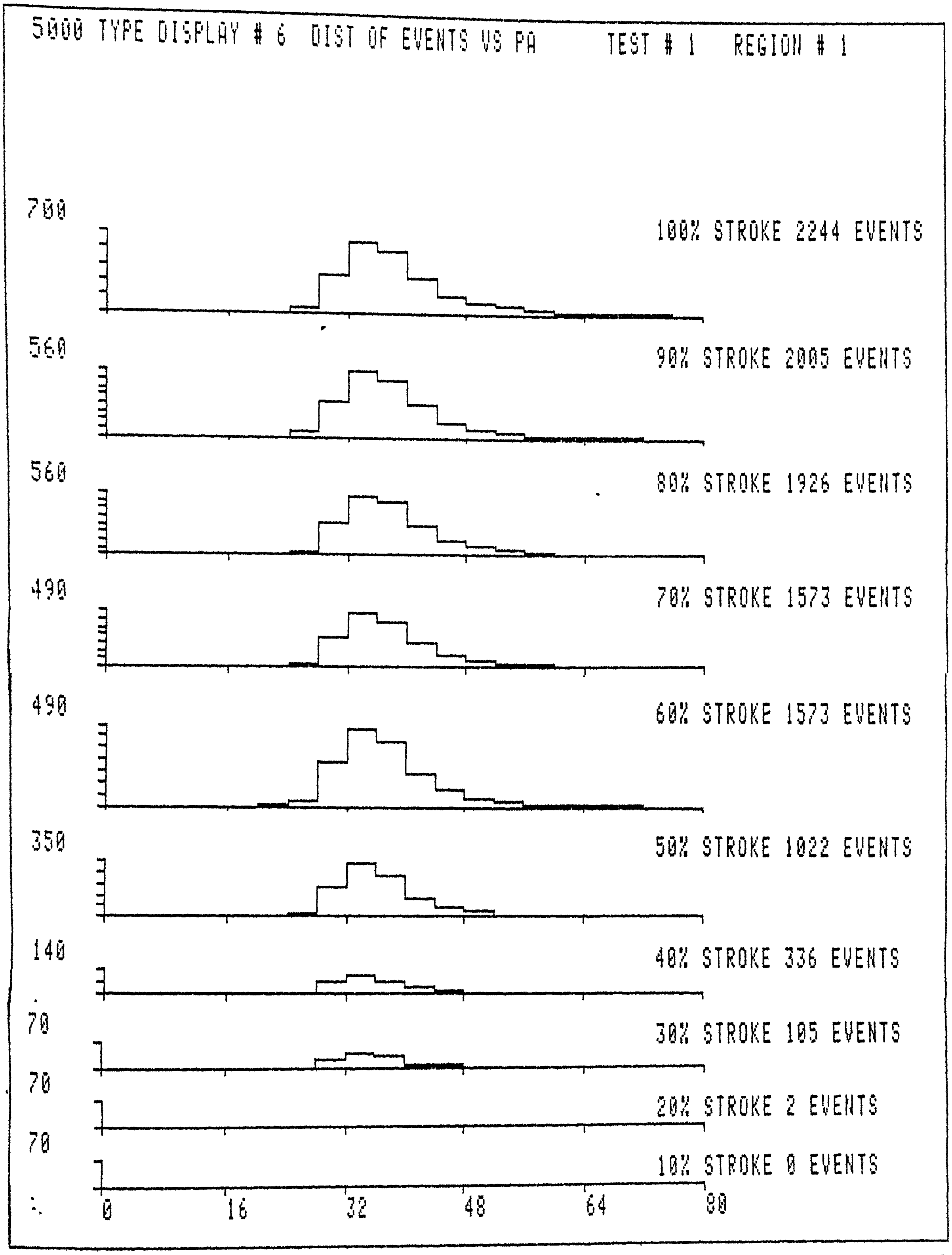


Fig. 5.23 Distribution of events vs peak amplitude of $[45_{12}]$ laminate.

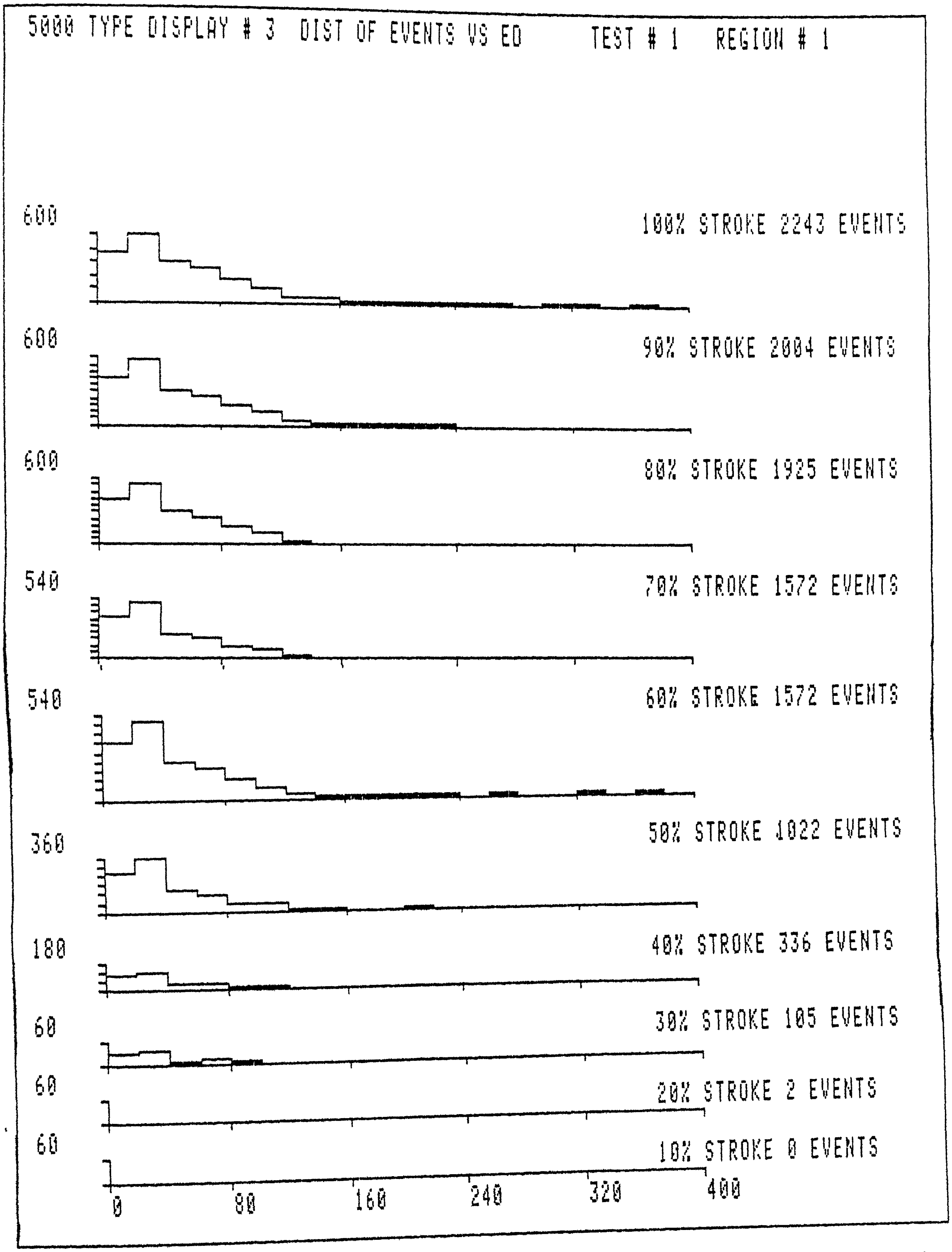


Fig. 5.24 Distribution of events vs event duration of $[45_{12}]$ laminate.

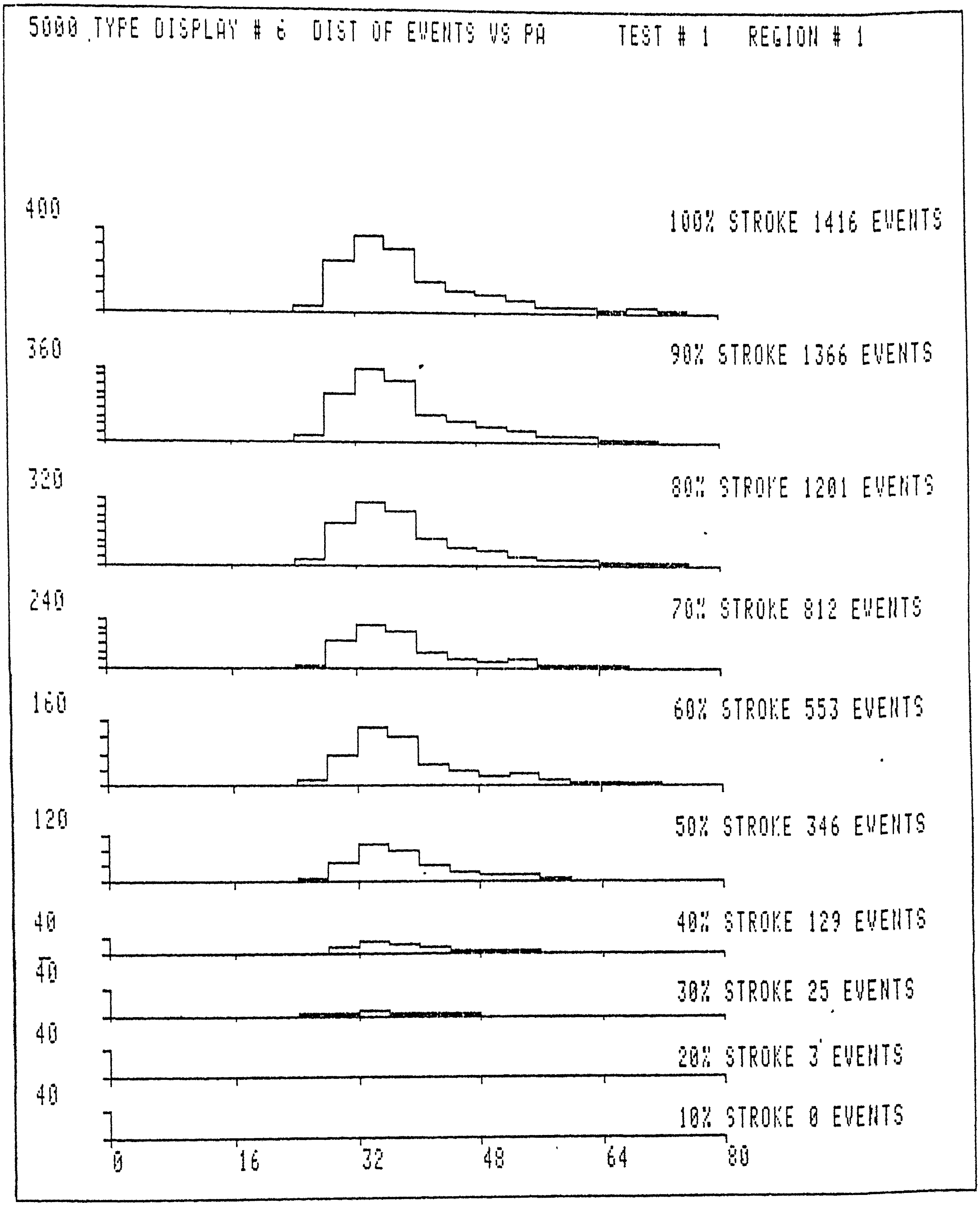


Fig. 5.25 Distribution of events vs peak amplitude of $[90_{12}]$ laminate.

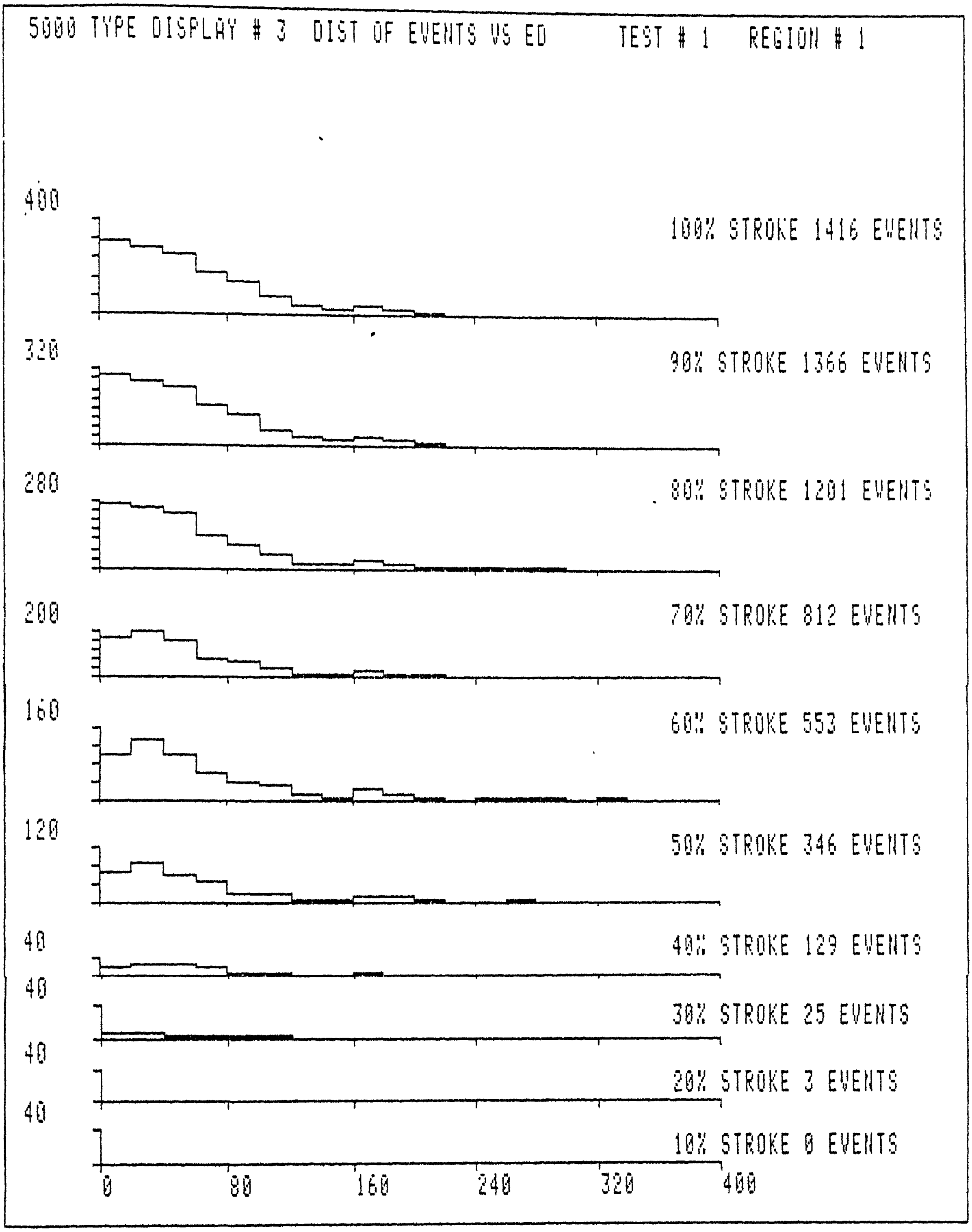


Fig. 5.26 Distribution of events vs event duration of $[90_{12}]$ laminate.

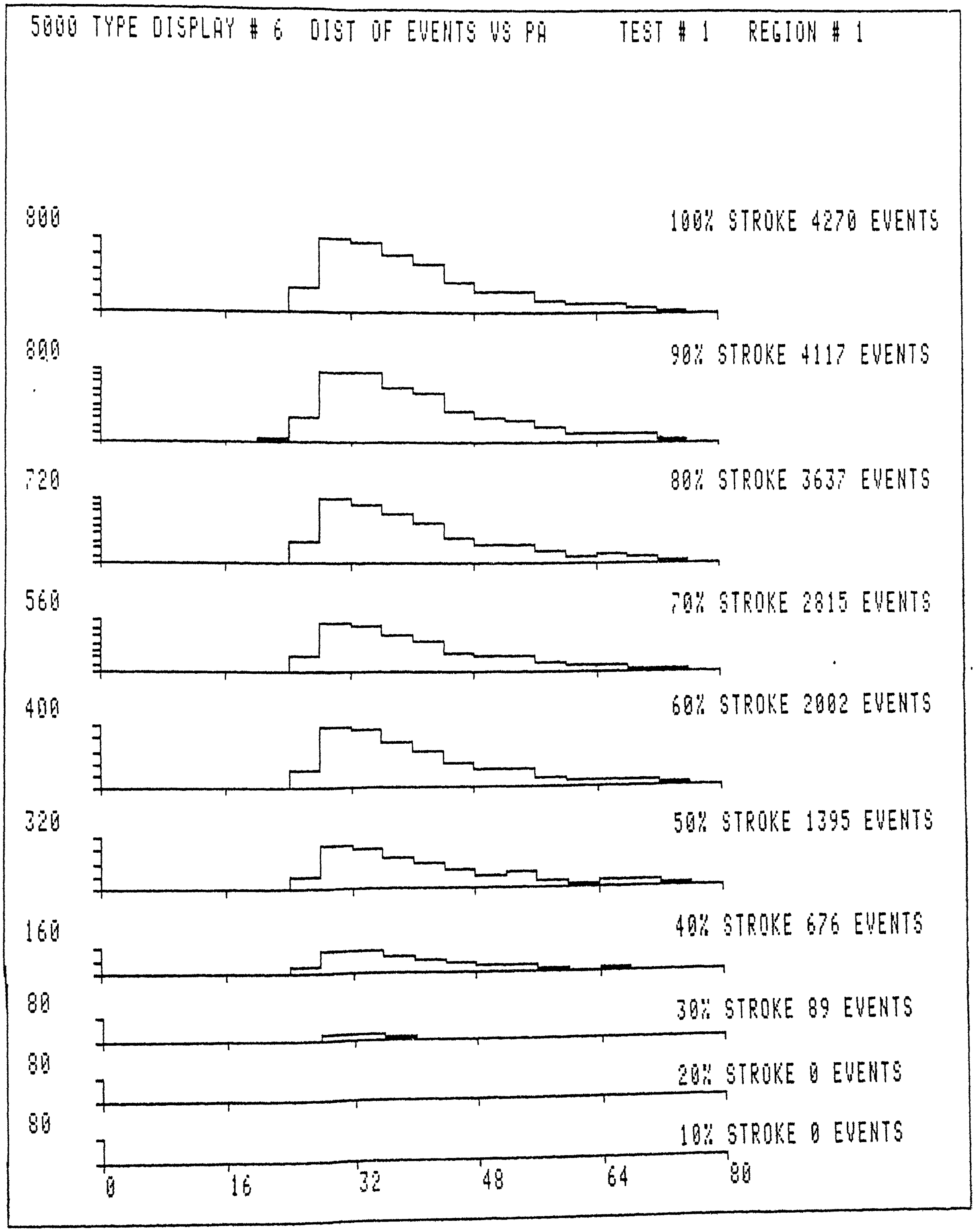


Fig. 5.27 Distribution of events vs peak amplitude of $[0_3/90_3]_S$ laminate.

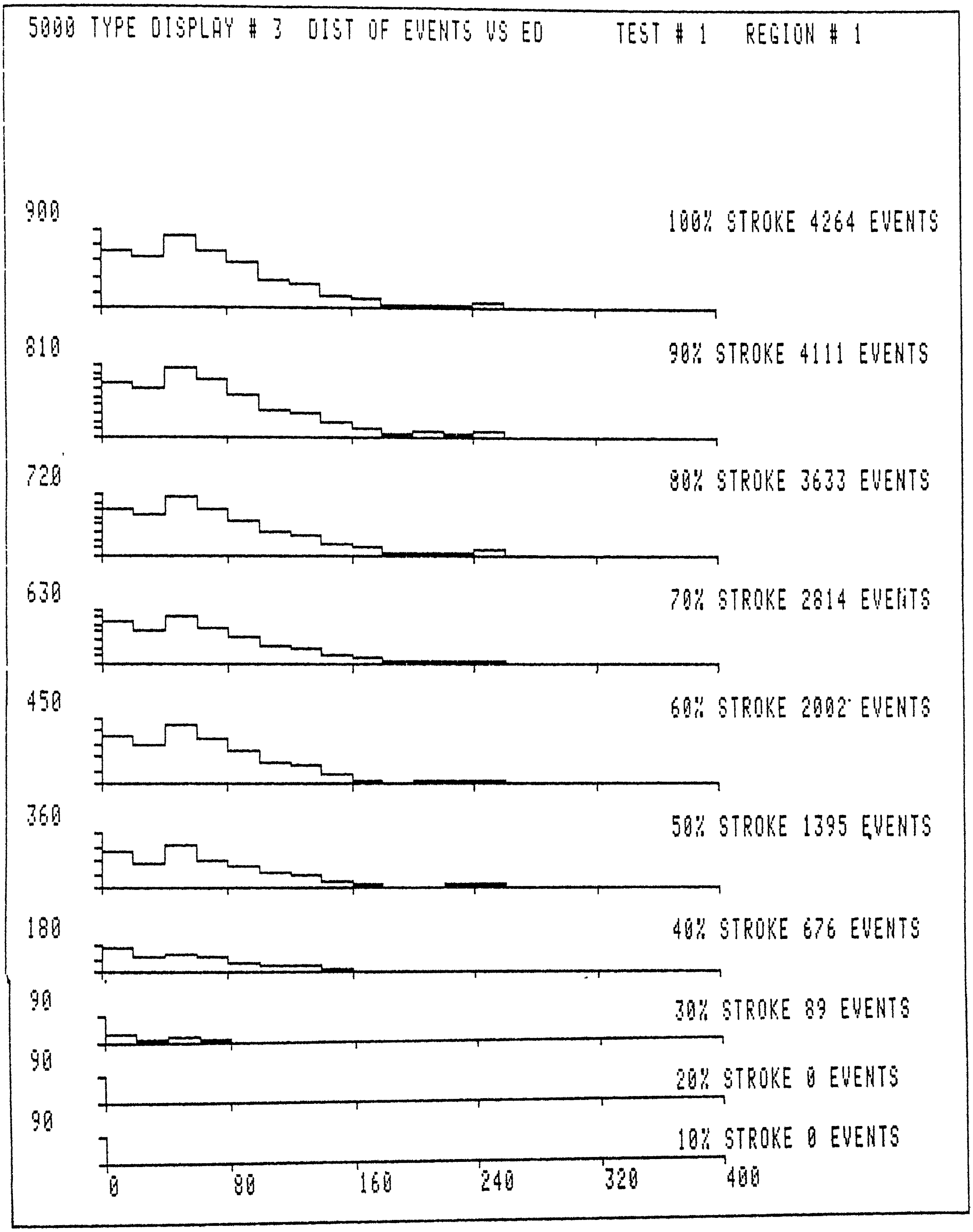


Fig. 5.28 Distribution of events vs event duration of $[0_3/90_3]_S$ laminate.

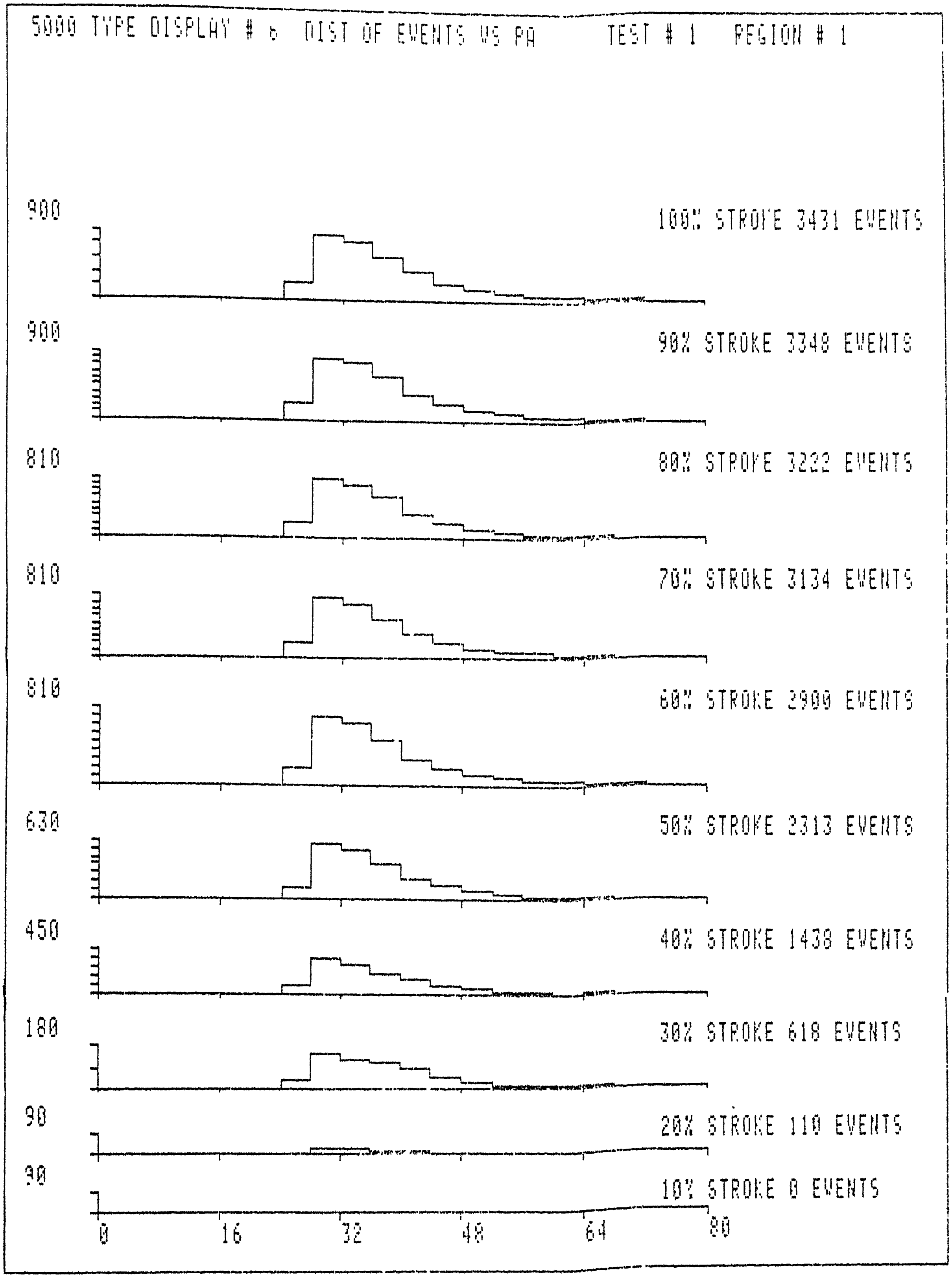


Fig. 5.29 Distribution of events vs peak amplitude of $[90_3/0_3]_S$ laminate.

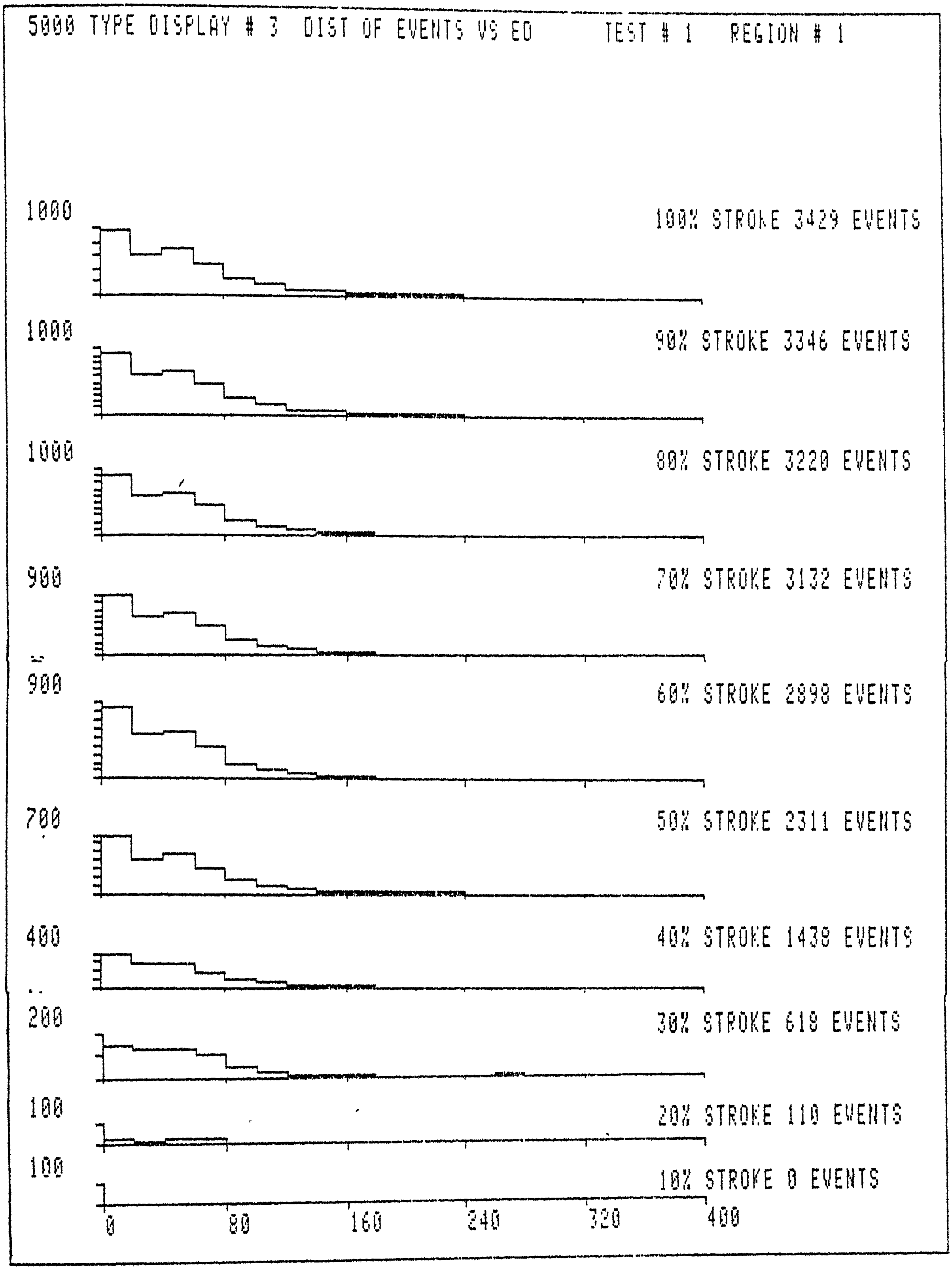


Fig. 5.30 Distribution of events vs event duration of $[90_3/0_3]_S$ laminate.

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS :

Acoustic Emission Technique to identify damage mechanisms of Kevlar / epoxy composites has been investigated experimentally. Emphasis was placed on developing special softwares for AE data analysis. While testing for AE in Kevlar epoxy composites, attention was focussed on :

1. Selection of appropriate AE parameters that influence the damage mechanism, viz. Fiber failure, Matrix failure, Interface failure; in composites through statistical methods.
2. Quantitatively obtain AE parameter values influencing fiber failure and matrix failure by studying AE characteristic of pure epoxy and fiber rich laminate.
3 Apply the quantitative results of fiber and matrix study to composite laminates and classify the damage modes.

Based on the observations made the following conclusions are drawn.

1. Acoustic Emission is capable of characterizing events associated with different damage mechanism in composites. With the flexibility to analyze real time data using user coded softwares, the technique stands to prove as a viable method for Non-destructive evaluation.

2. Softwares have been developed to perform all the conventional AE data analysis such as listing of event output, two dimensional histogram plots at different load or stroke levels, generating crossplots between two AE parameters with wide provision for

selection by the experimenter. In addition , a general purpose statistical analysis routine has been developed to classify AE parameters of importance

3 It has been shown through statistical analysis that two parameters of AE data , Peak amplitude and Event duration are best indicators for characterizing the damage mechanisms. Ringdown counts and Rise time do not have the distinguishing ability to separate the failure modes. The statistical variation in Skewness and Kurtosis for RDC and RT substantiate the above fact.

4. For Kevlar epoxy composites with fiber volume fraction of 55%, crowfeet weave, it has been shown that fiber failure is represented by events falling outside $\bar{X} \pm \sigma$ of peak amplitude as well as of event duration. Also matrix failure is represented by events falling inside $\bar{X} - \sigma$ of peak amplitude as well as of event duration.The region between $\pm \sigma$ is considered as interface failure and classification into other damage modes in this region needs further investigation.

5. Though peak amplitude and event duration have shown a base for understanding matrix damage and fiber damage, further in-depth study to classify the various interface damage mechanism is required.

6. File transfer from CP/M system to MS-DOS system has been well initiated leading a way for efficient data processing through well known high level languages.

6.2 SCOPE FOR FUTURE WORK :

The present work has been a base to develop a methodology to monitor and classify damage mechanism in Kevlar /epoxy composites. The identification of different interface failure mechanisms needs detailed study through pattern recognition technique, cluster analysis and frequency analysis.

The developed softwares for AE data handling can be extended to include other cluster analysis procedure there by establishing correspondence between AE intensities and specific interface failure process.

AE with Ultrasonics (Acousto-Ultrasonics) study can help in detecting and sizing of crack like defects Application of AE to cylindrical specimens will prove a long way indicating AE as a potential Non-Destructive Evaluation Technique.

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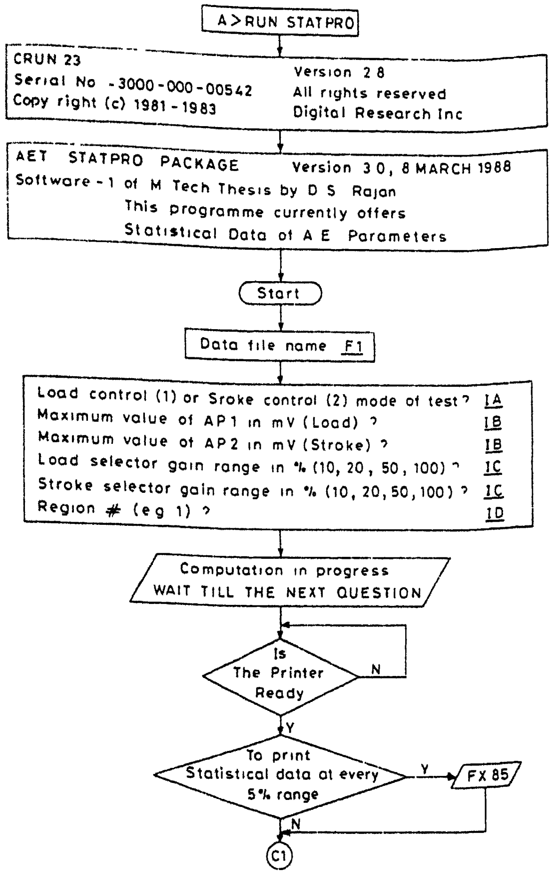
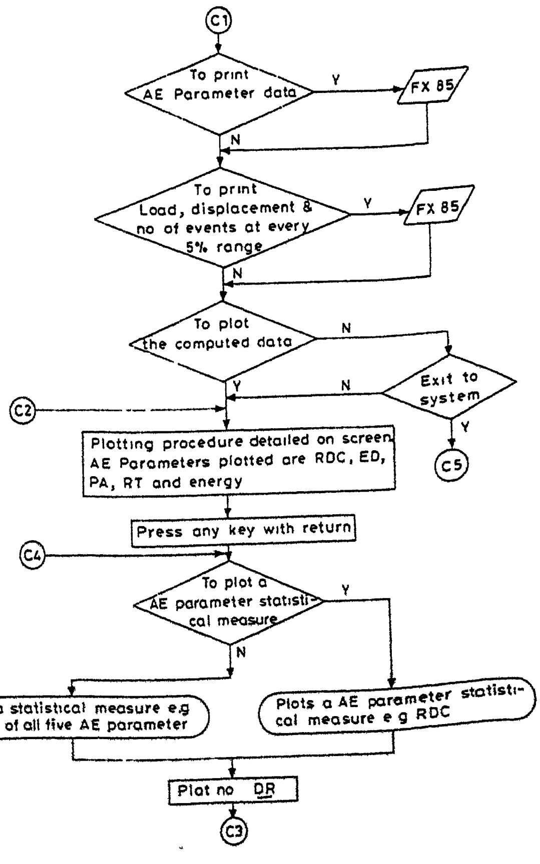
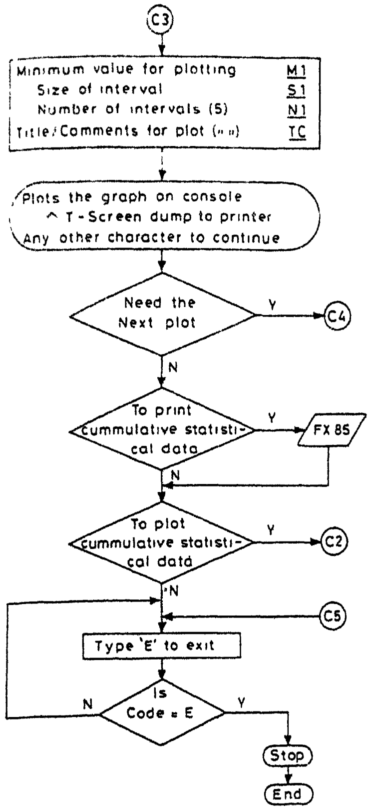
APPENDIX - B

Flow Chart and Sample Dialogue for 'STATPRO' Program.


A>RUN STATPRO
CRUN 23
Serial No -3000-000-00542
Copy right (c) 1981-1983
Version 2 8
All rights reserved
Digital Research Inc
AET STATPRO PACKAGE Version 3 0, 8 MARCH 1988
Software-1 of M Tech Thesis by D S Rajan
This programme currently offers
Statistical Data of A E Parameters
Start
Data file name F1
Load control (1) or Sroke control (2) mode of test ? IA
Maximum value of AP1 in mV (Load) ? IB
Maximum value of AP2 in mV (Stroke) ? IB
Load selector gain range in % (10, 20, 50, 100) ? IC
Stroke selector gain range in % (10, 20, 50, 100) ? IC
Region # (e g 1) ? ID
Computation in progress
WAIT TILL THE NEXT QUESTION
Is The Printer Ready
N
Y
To print Statistical data at every 5% range
Y
FX 85
N
C1


C1
To print AE Parameter data
Y
FX 85
N
To print Load, displacement & no of events at every 5% range
Y
FX 85
N
To plot the computed data
N
Exit to system
N
Y
C2
Y
C5
Plotting procedure detailed on screen
AE Parameters plotted are RDC, ED, PA, RT and energy
Press any key with return
C4
To plot a AE parameter statistical measure
Y
N
Plot a statistical measure e g mean of all five AE parameter
Plots a AE parameter statistical measure e g RDC
Plot no DR
C3



C3
Minimum value for plotting M1
Size of interval S1
Number of intervals (5) N1
Title/Comments for plot ("") TC
Plots the graph on console
^ T - Screen dump to printer
Any other character to continue
Need the Next plot
Y
C4
N
To print cummulative statistical data
Y
FX 85
N
To plot cummulative statistical data
Y
C2
N
C5
Type 'E' to exit
Is Code = E
N
Y
Stop
End

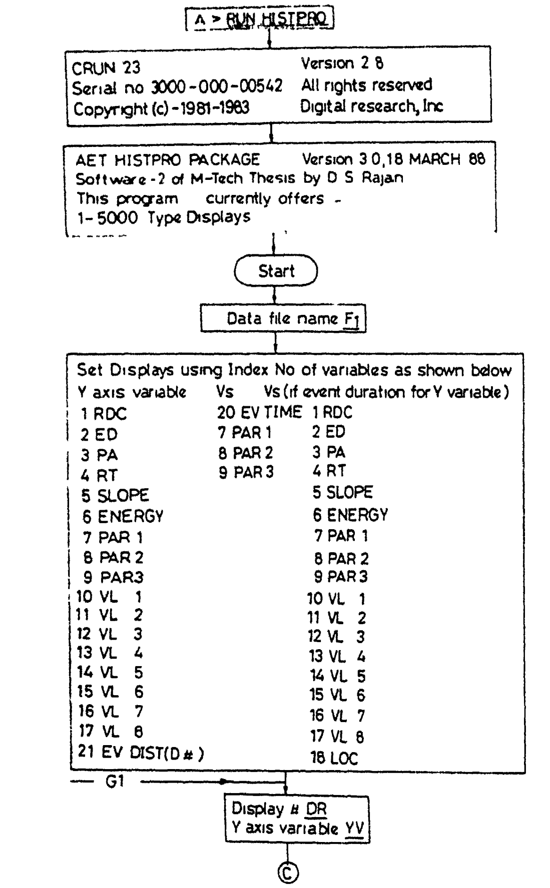
DIALOGUE FOR STATISTICAL DATA

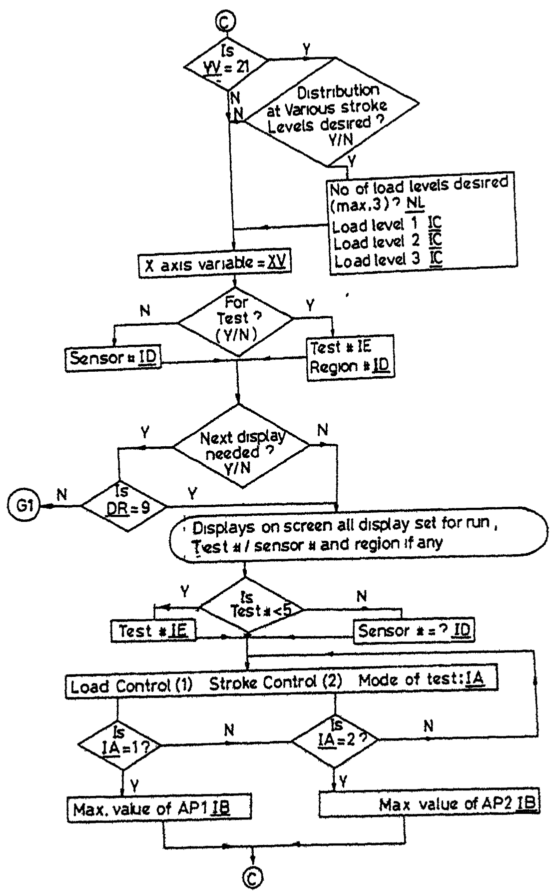
```
A > RUN STATPRO
 -----------------------------------------------------
 CRUN23                                    Version 2.8
 Serial No. 3000-0000-005420     All rights reserved
 Copyright (c) 1981-1983       Digital Research, Inc.
 -----------------------------------------------------
 AET STATPRO PACKAGE VERSION 3.0, 8 MARCH 1988.
 SOFTWARE-1 OF M.TECH THESIS BY D.S.RAJAN.

 THIS PROGRAM CURRENTLY OFFERS ONE OUTPUT OPTION:
  1. 'STATISTICAL DATA OF AE PARAMETERS'
 DATA FILE NAME:  Z.D01
 LOAD CONTROL(1)/STROKE CONTROL(2) MODE OF TEST 2
 MAX VALUE OF AP1 IN MV 50
 MAX VALUE OF AP2 IN MV 40
 LOADING RATE % (10,20,50,100): 10
 DISPLACEMENT RATE % (10,20,50,100): 10
 REGION # 3
 WAIT TILL THE NEXT QUESTION


 IS THE PRINTER READY(Y/N)? N
 IS THE PRINTER READY(Y/N)? Y
 TO PRINT OUTPUT BETWEEN LOAD/STROKE LEVELS:(Y/N) YN

 TO PRINT AE PARAMETER DATA?(Y/N) N
 TO PRINT LOAD/STROKE LEVEL & NO OF EVENTS?(Y/N) N
 TO PLOT THE COMPUTED DATA:?(Y/N) Y
                       *******************PLOTING PROCEDURE****************
                       *                                                  *
                       * THE DATA COMPUTED CAN BE REPRESENTED GRAPHICALLY. *
                       * FOUR PLOTS CAN BE PLOTED BETWEEN RANGES AND FOUR  *
                       * PLOTS FOR CUMMULATIVE VALUES.THIS IS DONE IN TWO  *
                       * STAGES.RANGE PLOTS IN STAGE 1 & CUMMULATIVE PLOTS *
                       * IN STAGE 2.IN BOTH CASES YOUR RESPONCE TO PLOT NO *
                       * WILL HAVE A DIRECT RELATION TO THE PLOTING Y-AXIS *
                       * PARAMETER.THE INDEX REF. FOR PLOT NO'S ARE :-     *
                       * 1 - PLOT OF MEAN VS LOAD/STROKE%.                 *
                       * 2 - PLOT OF STANDARD DEVIATION VS LOAD/STROKE%.   *
                       * 3 - PLOT OF SKEWNESS VS LOAD/STROKE%.             *
                       * 4 - PLOT OF KURTOSIS VS LOAD/STROKE%.             *
                       * GIVE THE CORRESPONDING NO IN RESPONCE TO   PROMPT.*
                       *     THE END OF A PLOT IS INDICATED BY THE CURSOR  *
                       * POSITION JUST ABOVE THE LOWER LEFT CORNER.  FIRST *
                       * FIRST TAKE HARDCOPY,THEN PRESS ANY  KEY  FOLLOWED *
                       * BY A RETURN TO CONTINUE.                          *
                       *                                                  *
                       ****************************************************
```

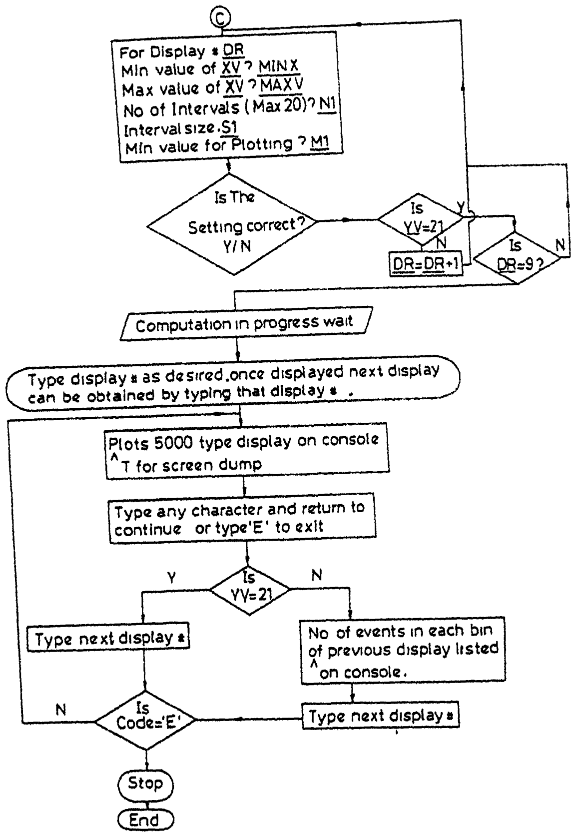
```
  A
PLOT NO 1
TO PLOT A SINGLE AE PARAMETER W.R.T LOAD/STROKE%(Y/N)? Y
MINVALUE ALONG Y AXIS: 0
NO OF INTERVALS: 5
SIZE OF INTERVAL: 5
TITTLE FOR THE PLOT(WITHIN "): "PLOT OF RDCFA MEASURTEE VS. STROKE% FOR SAZ.D01
SAM""


  A
DO YOU NEED THE NEXT PLOT?(Y/N): NY
PLOT NO 2
TO PLOT A SINGLE AE PARAMETER W.R.T LOAD/STROKE%(Y/N)? N
MINVALUE ALONG Y AXIS: 0
NO OF INTERVALS: 5
SIZE OF INTERVAL: 5
TITTLE FOR THE PLOT(WITHIN "): "PLOT OF MEAN VS.STROKE% FOR SAZ.D01"


  A
DO YOU NEED THE NEXT PLOT?(Y/N): N
TO EXIT OUT OF SYSTEM?(Y/N): N
TO PRINT CUMMULATIVE STATISTICAL DATA?:(Y/N) N
TO PLOT CUMMULATIVE STATISTICAL DATA?(Y/N): Y
                    *******************PLOTING PROCEDURE****************
                    *                                                  *
                    * THE DATA COMPUTED CAN BE REPRESENTED GRAPHICALLY. *
                    * FOUR PLOTS CAN BE PLOTED BETWEEN RANGES AND FOUR  *
                    * PLOTS FOR CUMMULATIVE VALUES.THIS IS DONE IN TWO  *
                    * STAGES.RANGE PLOTS IN STAGE 1 & CUMMULATIVE PLOTS *
                    * IN STAGE 2.IN BOTH CASES YOUR RESPONCE TO PLOT NO *
                    * WILL HAVE A DIRECT RELATION TO THE PLOTING Y-AXIS *
                    * PARAMETER.THE INDEX REF. FOR PLOT NO'S ARE :-     *
                    * 1 - PLOT OF MEAN VS LOAD/STROKE%.                 *
                    * 2 - PLOT OF STANDARD DEVIATION VS LOAD/STROKE%.   *
                    * 3 - PLOT OF SKEWNESS VS LOAD/STROKE%.             *
                    * 4 - PLOT OF KURTOSIS VS LOAD/STROKE%.             *
                    * GIVE THE CORRESPONDING NO IN RESPONCE TO   PROMPT.*
                    *     THE END OF A PLOT IS INDICATED BY THE CURSOR  *
                    * POSITION JUST ABOVE THE LOWER LEFT CORNER.  FIRST *
                    * FIRST TAKE HARDCOPY,THEN PRESS ANY  KEY  FOLLOWED *
                    * BY A RETURN TO CONTINUE.                          *
                    *                                                  *
                    ****************************************************
  A
PLOT NO 1
TO PLOT A SINGLE AE PARAMETER W.R.T LOAD/STROKE%(Y/N)? N
MINVALUE ALONG Y AXIS: 0
NO OF INTERVALS: 5
SIZE OF INTERVAL: 20
TITTLE FOR THE PLOT(WITHIN "): "CUMULATIVE PLOT OF MEAN FORN SAZ.D01"
  A
DO YOU NEED THE NEXT PLOT?(Y/N): N
TO EXIT OUT OF SYSTEM?(Y/N): Y
TYPE 'E' TO EXIT FROM SYSTEM E
```

APPENDIX - C

Flow Chart and Sample Dialogue for 'HISTPRO' Program.


A > RUN HISTPRO
CRUN 23
Serial no 3000-000-00542
Copyright (c)-1981-1983
Version 2 8
All rights reserved
Digital research, Inc
AET HISTPRO PACKAGE Version 3 0,18 MARCH 88
Software-2 of M-Tech Thesis by D S Rajan
This program currently offers -
1-5000 Type Displays
Start
Data file name F1
Set Displays using Index No of variables as shown below
Y axis variable Vs Vs (if event duration for Y variable)
1 RDC 20 EV TIME 1 RDC
2 ED 7 PAR 1 2 ED
3 PA 8 PAR 2 3 PA
4 RT 9 PAR 3 4 RT
5 SLOPE 5 SLOPE
6 ENERGY 6 ENERGY
7 PAR 1 7 PAR 1
8 PAR 2 8 PAR 2
9 PAR3 9 PAR3
10 VL 1 10 VL 1
11 VL 2 11 VL 2
12 VL 3 12 VL 3
13 VL 4 13 VL 4
14 VL 5 14 VL 5
15 VL 6 15 VL 6
16 VL 7 16 VL 7
17 VL 8 17 VL 8
21 EV DIST(D #) 18 LOC
G1
Display # DR
Y axis variable YV
C


C
Is YV = 21
Y
N
N
Distribution at Various stroke Levels desired ? Y/N
Y
No of load levels desired (max.3) ? NL
Load level 1 IC
Load level 2 IC
Load level 3 IC
X axis variable = XV
For Test ? (Y/N)
N
Y
Sensor # ID
Test # IE
Region # ID
Next display needed ? Y/N
Y
N
G1
N
Is DR=9
Y
Displays on screen all display set for run, Test # / sensor # and region if any
Is Test # <5
Y
N
Test # IE
Sensor # = ? ID
Load Control (1) Stroke Control (2) Mode of test: IA
Is IA=1?
N
Is IA=2 ?
N
Y
Y
Max. value of AP1 IB
Max value of AP2 IB
C


C
For Display # DR
Min value of XV ? MINX
Max value of XV ? MAXV
No of Intervals (Max 20)? N1
Interval size ,S1
Min value for Plotting ? M1
Is The Setting correct? Y/N
Is YV=21
Y
N
DR=DR+1
Is DR=9 ?
N
Computation in progress wait
Type display # as desired,once displayed next display can be obtained by typing that display # .
Plots 5000 type display on console ^T for screen dump
Type any character and return to continue or type'E' to exit
Is YV=21
Y
N
Type next display #
No of events in each bin of previous display listed on console.
N
Is Code='E'
Type next display #
Stop
End

DIALOGUE FOR HISTOGRAM PLOTS

```
A>RUN HISTPRO
----------------------------------------------------------
CRUN23                                        Version 2.8
Serial No. 3000-0000-005420      All rights reserved
Copyright (c) 1981-1983        Digital Research, Inc.
----------------------------------------------------------
AET HISTPRO PACKAGE    VERSION 3.0 , 10 MARCH 1988
SOFTWARE - 2 OF M.TECH. THESIS BY D.S.RAJAN

THE PROGRAM OFFERS ONE  OPTION:
 1. 5000-TYPE OF DISPLAYS

DATA FILE NAME:  Z.D01
5000-TYPE OF DISPLAYS? Y
SET DISPLAYS USING INDEX NUMBERS OF VARIABLES AS SHOWN BELOW:
Y AXIS VARIABLE      VS
                                    VS(IF EVENT DISTRIBUTION FOR Y VARIABLE)
 1 RDC               20 EVENT TIME     1 RDC
 2 ED                 7 PAR 1          2 ED
 3 PA                 8 PAR 2          3 PA
 4 RT                 9 PAR 3          4 RT
 5 SLOPE                               5 SLOPE
 6 ENERGY                              6 ENERGY
 7 PAR 1                               7 PAR 1
 8 PAR 2                               8 PAR 2
 9 PAR 3                               9 PAR 3
 10 VL 1                               10 VL 1
 11 VL 2                               11 VL 2
 12 VL 3                               12 VL 3
 13 VL 4                               13 VL 4
 14 VL 5                               14 VL 5
 15 VL 6                               15 VL 6
 16 VL 7                               16 VL 7
 17 VL 8                               17 VL 8
 21 EV DIST(D#)                        18 LOC
DISPLAY #  1
Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) Y
NUMBER OF DIFFERENT STROKE LEVELS DESIRED(MAXM 3) 3
TYPE IN VARIOUS STROKE LEVELS IN RESPONSE TO PROMPT-?
SHOULD BE AN  INTEGER FOLLOWED BY RETURN KEY STROKE
? 10
? 20
? 30
FOR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE
OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC
X AXIS VARIABLE?  3
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  2

Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) Y
```

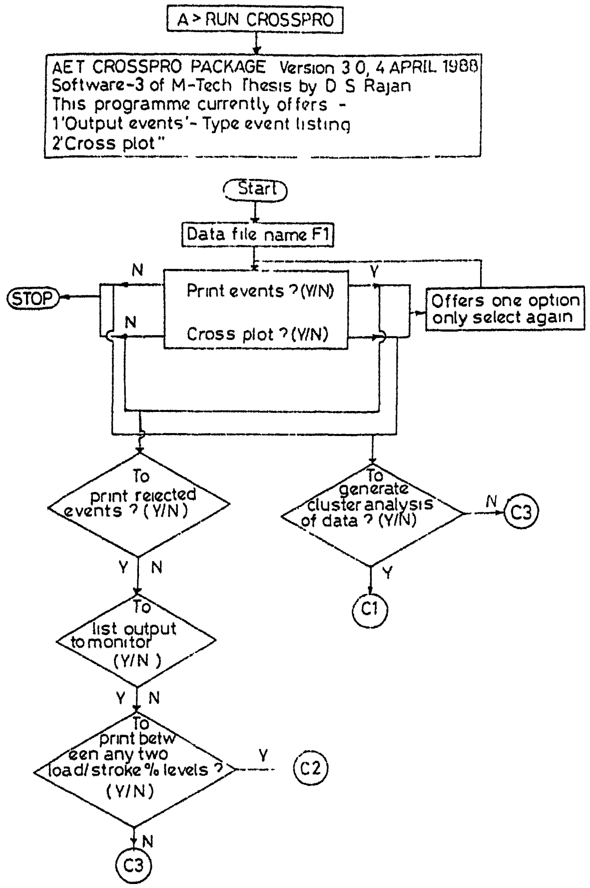
```
NUMBER OF DIFFERENT STROKE LEVELS DESIRED(MAXM 3) 3
TYPE IN VARIOUS STROKE LEVELS IN RESPONSE TO PROMPT-?
SHOULD BE AN  INTEGER FOLLOWED BY RETURN KEY STROKE
? 40
? 50
? 60
FOR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE
OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC
X AXIS VARIABLE?  3
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  3
Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) Y
NUMBER OF DIFFERENT STROKE LEVELS DESIRED(MAXM 3) 3
TYPE IN VARIOUS STROKE LEVELS IN RESPONSE TO PROMPT-?
SHOULD BE AN  INTEGER FOLLOWED BY RETURN KEY STROKE
? 70
? 80
? 90
FOR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE
OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC
X AXIS VARIABLE?  3
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 1
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  4
Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) YY
NUMBER OF DIFFERENT STROKE LEVELS DESIRED(MAXM 3) 3
TYPE IN VARIOUS STROKE LEVELS IN RESPONSE TO PROMPT-?
SHOULD BE AN  INTEGER FOLLOWED BY RETURN KEY STROKE
? 25
? 50
? 75
FOR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE
OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC
X AXIS VARIABLE?  2
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  5
Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) N
X AXIS VARIABLE?  1
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3

NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  6
Y AXIS VARIABLE?  27
SCALE: 1 MILLIVOLT = (WITHOUT UNITS) 10
X AXIS VARIABLE?  8
SCALE: 1 MILLIVOLT = (WITHOUT UNITS) 10
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
```

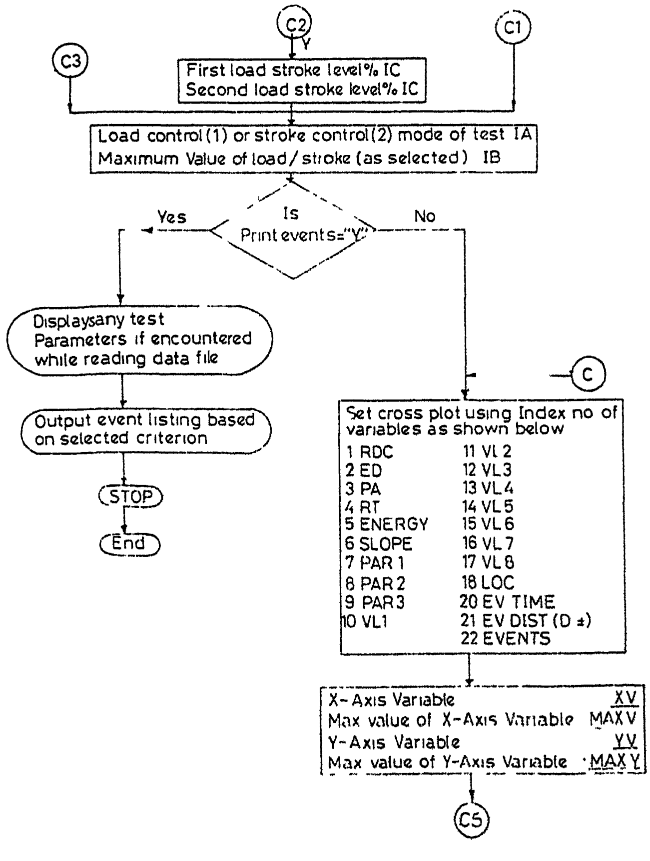
```
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  7
Y AXIS VARIABLE?  32
X AXIS VARIABLE?  3
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  8
Y AXIS VARIABLE?  3
X AXIS VARIABLE?  6
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
NEXT DISPLAY NEEDED ?(Y/N)   Y
DISPLAY #  9
Y AXIS VARIABLE?  21
DIST AT VARIOUS STROKE LEVELS DESIRED ?(Y/N) Y
NUMBER OF DIFFERENT STROKE LEVELS DESIRED(MAXM 3) 3
TYPE IN VARIOUS STROKE LEVELS IN RESPONSE TO PROMPT-?
SHOULD BE AN  INTEGER FOLLOWED BY RETURN KEY STROKE
? 20
? 40
? 60
FOR THIS TYPE OF DISPLAY X AXIS VARIABLE CAN BE ONE
OF THE FOLLOWING - RDC,ED,PA,RT,SLOPE,ENERGY & LOC
X AXIS VARIABLE?  20
FOR TEST? (Y/N) Y
TEST #? 1
REGION #? 3
DISPLAYS SET FOR THE RUN
 1 DIST OF EVENTS  VS  PA              TEST #  1          REGION #  3
 2 DIST OF EVENTS  VS  PA              TEST #  1          REGION #  3
 3 DIST OF EVENTS  VS  PA              TEST #  1          REGION #  1
 4 DIST OF EVENTS  VS  ED              TEST #  1          REGION #  3
 5 DIST OF EVENTS  VS  RDC             TEST #  1          REGION #  3
 6 PAR 1     VS  PAR 2                 TEST #  1          REGION #  3
 7 ED        VS  PA                    TEST #  1          REGION #  3
 8 PA        VS  ENERGY                TEST #  1          REGION #  3
 9 DIST OF EVENTS  VS  EVENT TIME      TEST #  1          REGION #  3
LOAD CONTROL(1)/STROKE CONTROL(2) TEST?: 2
MAX VALUE OF AP2 40
FOR DISPLAY #  1
MIN VALUE OF PA
MIN VALUE :  0
MAX VALUE OF PA
MAX VALUE :  25
NO  OF INTERVALS (MAX 20)? 15
INTERVAL SIZE ?  2
MIN  VALUE FOR PLOTTING ? 0
FOR DISPLAY #  2
MIN VALUE OF PA
MIN VALUE :  0
MAX VALUE OF PA
MAX VALUE :  40
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  2
MIN  VALUE FOR PLOTTING ? 0
FOR DISPLAY #  3
MIN VALUE OF PA
```

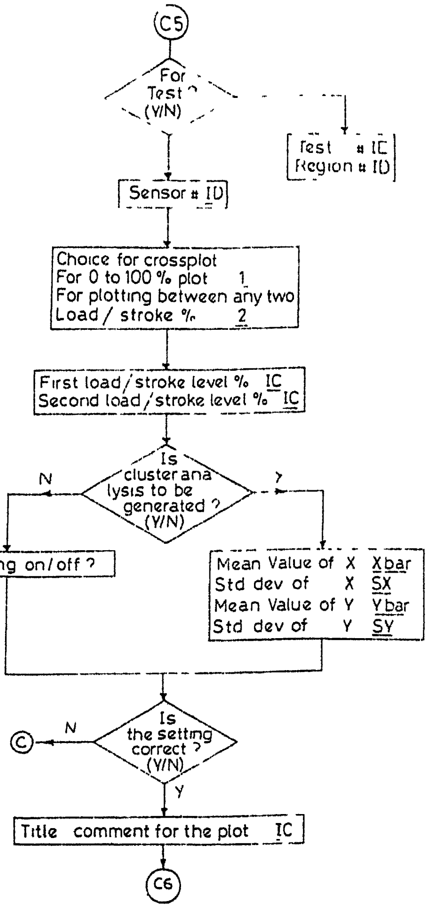
```
MIN VALUE :  10
MAX VALUE OF PA
MAX VALUE :  30
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  1
MIN  VALUE FOR PLOTTING ? 10
FOR DISPLAY #  4
MIN VALUE OF ED
MIN VALUE :  0
MAX VALUE OF ED
MAX VALUE :  25020
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  11
MIN  VALUE FOR PLOTTING ? 0
FOR DISPLAY #  5
MIN VALUE OF RDC
MIN VALUE :  0
MAX VALUE OF RDC
MAX VALUE :  50
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  3
MIN  VALUE FOR PLOTTING ? 0
FOR DISPLAY #  6
MIN VALUE OF PAR 2
MIN VALUE :  0
MAX VALUE OF PAR 2
MAX VALUE :  40
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  2
MIN  VALUE FOR PLOTTING ? 0
FOR DISPLAY #  7
MIN VALUE OF PA
MIN VALUE :  05
MAX VALUE OF PA
MAX VALUE :  25
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  1
MIN  VALUE FOR PLOTTING ? 10
NEED AVERAGE PLOT ? (1/2): 1
FOR DISPLAY #  8
MIN VALUE OF ENERGY
MIN VALUE :  0
MAX VALUE OF ENERGY
MAX VALUE :  100
NO  OF INTERVALS (MAX 20)? 20
INTERVAL SIZE ?  5
MIN  VALUE FOR PLOTTING ? 0
NEED AVERAGE PLOT ? (1/2): 2
FOR DISPLAY #  9
MIN VALUE OF EVENT TIME
MIN VALUE :  0
MAX VALUE OF EVENT TIME
MAX VALUE :  15
NO  OF INTERVALS (MAX 20)? 15
INTERVAL SIZE ?  1
MIN  VALUE FOR PLOTTING ? 0

TYPE DISPLAY # AS DESIRED. ONCE  DISPLAYED NEXT  DISPLAY
CAN BE OBTAINED BY TYPING THAT DISPLAY #. TYPE E TO EXIT
```

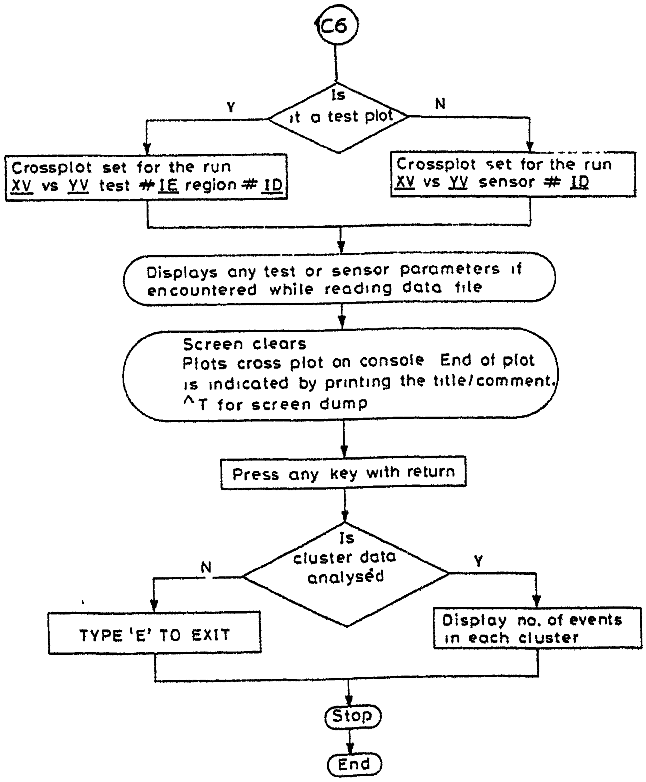
APPENDIX - D

Flow Chart and Sample Dialogue for 'CROSSPRO' Program.


A > RUN CROSSPRO
AET CROSSPRO PACKAGE Version 3 0, 4 APRIL 1988
Software-3 of M-Tech Thesis by D S Rajan
This programme currently offers -
1'Output events'- Type event listing
2'Cross plot"
Start
Data file name F1
N
Y
STOP
Print events ? (Y/N)
N
Cross plot ? (Y/N)
Offers one option only select again
To print rejected events ? (Y/N)
Y
N
To generate cluster analysis of data ? (Y/N)
N
C3
Y
C1
To list output to monitor (Y/N)
Y
N
To print between any two load/stroke % levels ? (Y/N)
Y
C2
N
C3


C2
Y
C1
C3
First load stroke level% IC
Second load stroke level% IC
Load control(1) or stroke control(2) mode of test IA
Maximum Value of load / stroke (as selected) IB
Yes
Is Print events="Y"
No
Displaysany test Parameters if encountered while reading data file
C
Output event listing based on selected criterion
Set cross plot using Index no of variables as shown below
1 RDC
2 ED
3 PA
4 RT
5 ENERGY
6 SLOPE
7 PAR 1
8 PAR 2
9 PAR3
10 VL1
11 VL 2
12 VL3
13 VL4
14 VL5
15 VL6
16 VL7
17 VL8
18 LOC
20 EV TIME
21 EV DIST (D ±)
22 EVENTS
STOP
End
X-Axis Variable XV
Max value of X-Axis Variable MAXV
Y-Axis Variable YV
Max value of Y-Axis Variable MAXY
C5


C5
For Test? (Y/N)
Test # IC
Region # ID
Sensor # ID
Choice for crossplot
For 0 to 100 % plot 1
For plotting between any two
Load / stroke % 2
First load/stroke level % IC
Second load/stroke level % IC
Is cluster analysis to be generated ? (Y/N)
N
Y
Line drawing on/off ?
Mean Value of X Xbar
Std dev of X SX
Mean Value of Y Ybar
Std dev of Y SY
Is the setting correct ? (Y/N)
N
C
Y
Title comment for the plot IC
C6


C6
Is it a test plot
Y
N
Crossplot set for the run
XV vs YV test # IE region # ID
Crossplot set for the run
XV vs YV sensor # ID
Displays any test or sensor parameters if encountered while reading data file
Screen clears
Plots cross plot on console End of plot is indicated by printing the title/comment.
^T for screen dump
Press any key with return
Is cluster data analysed
N
Y
TYPE 'E' TO EXIT
Display no. of events in each cluster
Stop
End

DIALOGUE FOR CROSSPLOT

```
                    A>RUN CROSSPRO
---------------------------------------------------------------
CRUN23                                          Version 2.8
Serial No. 3000-0000-005420       All rights reserved
Copyright (c) 1981 1982       Digital Research, Inc.
---------------------------------------------------------------
AET CROSSPRO PACKAGE    VERSION 3.0, 4 APRIL 1988
SOFTWARE - 3 OF M.TECH. THESIS BY D.S.RAJAN.

THIS PROGRAM OFFERS ONE OF THE FOLLOWING OPTIONS:
 1. 'OUTPUT EVENTS -TYPE EVENT LISTING
 2.  CROSSPLOT

DATA FILE NAME:  Z.D01
PRINT EVENTS? N
CROSSPLOT? Y
TO GENERATE CLUSTER ANALYSIS OF DATA ?(Y/N): N
LOAD CONTROL (1)/STROKE CONTROL (2) TEST?: 2
MAX VALUE OF AF2 IN MV 40
SET CROSSPLOT USING INDEX NUMBERS OF VARIABLES AS SHOWN BELOW:
 1 RDC
 2 ED
 3 PA
 4 RT
 5 SLOPE
 6 ENERGY
 7 PAR 1
 8 PAR 2
 9 PAR 3
 10 VL 1
 11 VL 2
 12 VL 3
 13 VL 4
 14 VL 5
 15 VL 6
 16 VL 7
 17 VL 8
 18 LOC
 20 EVENT TIME
 22 EVENTS
X AXIS VARIABLE ?  3
MAX.VALUE OF X AXIS VARIABLE? 80
Y AXIS VARIABLE ?  2
MAX. VALUE OF Y AXIS VARIABLE? 300
FOR TEST ? (Y/N) Y
TEST # ? 1
REGION #? 1
CROSS PLOT CAN BE OBTAINED IN 2 FORMS AS DETAILED
CHOICE NO.(1,2) 1
LINE DRAWING ? (ON/OFF): OFF
IS THE SETTING CORRECT?(Y/N): Y
TITLE/COMMENT FOR THE PLOT "SAMPLE PLOT FOR KEVLAR"
CROSSPLOT SET FOR THE RUN
ED       VS  PA       TEST #  1            REGION #  1
```

Date Slip

This book is to be returned on the date last stamped.
